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SURFACE CIRCULATION IN THE GULF OF MAINE AS DEDUCED FROM DRIFT BOTTLES

By C. Godfrey Day

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ABSTRACT

Drift-bottle returns from 17 cruises over the Gulf of Maine and Georges Bank are compared. Seasonal and year-to-year differences in surface water circulations are noted. Wind values for 60 days following each cruise are presented in an effort to determine wind influence on surface circulation within the area.

SURFACE CIRCULATION IN THE GULF OF MAINE AS DEDUCED FROM DRIFT BOTTLES

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Between 1931 and 1956, the United States Fish ıd Wildlife Service made a number of cruises to e Gulf of Maine and Georges Bank as part of a udy of the distribution and movement of the gs and larvae of commercially important food shes. On 17 of these cruises, during the years)31, 1932, 1933, 1934, 1953, 1955, and 1956, drift ottles were launched throughout the area.[1] The asonal coverage of these bottle seedings extends om late February through June.

Plots of drift-bottle returns showed such marked fferences that a careful analysis of these data as necessary. This paper reports the results of study of the surface circulations as deduced om bottle returns. Seasonal and year-to-year fferences are noted. Daily values for surface-ind direction and force for the period of each uise and for 60 days following have been taken om the daily weather maps in an effort to de-rmine the effect wind may have had on the sur-ıce-water movement.

The original data, the result of studies by the nited States Bureau of Fisheries and the United tates Fish and Wildlife Service, are on file at ıe Woods Hole Oceanographic Institution, where punchcard system is maintained and supple-ented as new drift-bottle returns are received nd further studies initiated.

The basic data used in the present paper are vailable in tabular form in Special Scientific Re-ort: Fisheries No. 242.

BOTTLE TYPES AND DISTRIBUTION

The bottles employed were those commonly used r carbonated drinks. They were of clear glass and measured approximately 22 cm. in height and 6 cm. in diameter, with a capacity of 8 fluid ounces.

Some of the bottles released on the 1931–34 cruises were equipped with drogues and some were not. The pattern of distribution during this period was confined to Georges and Browns Banks, but otherwise it followed no clear-cut system. Usually from 5 to 15 bottles were launched at a station, but occasionally they were distributed over a short track at the rate of 2 bottles every 2 miles. (These tracks of release are not indicated in the figures as they would needlessly confuse the drawing; all returns, however, are accounted for.)

During the 1953–56 cruises, half of the bottles were ballasted with dry sand so that they would float vertically at or near the surface; the other half contained no ballast. The bottles were distributed over a grid of stations fairly evenly covering the Gulf of Maine and Georges Bank. Twelve bottles were released at each station, 6 with ballast and 6 without.

INTERPRETATION OF DRIFT-BOTTLE RETURNS

The trajectories shown in the figures which follow represent general directional trends and in no case should they be considered to indicate the actual routes followed. For each bottle there are but two knowns with which to work: the place and date of launching and the place and date of recovery.

The method by which tracks were constructed from these meager data is best illustrated by an example. To this end, figure 1—*a*, *b*, *c*, and *d*—was prepared, showing the initial treatment of data from cruise 48 of the *Albatross III*.

The first step was to select the bottles with the shortest period of drift and plot their net movement by straight lines (fig. 1, *a*). Usually, as in

[1] Walford (1938) has discussed the results of the 1931 and 932 drift-bottle returns; the others have not previously been ported.

Note.—Approved for publication, September 30, 1957. Fishery lletin 141.

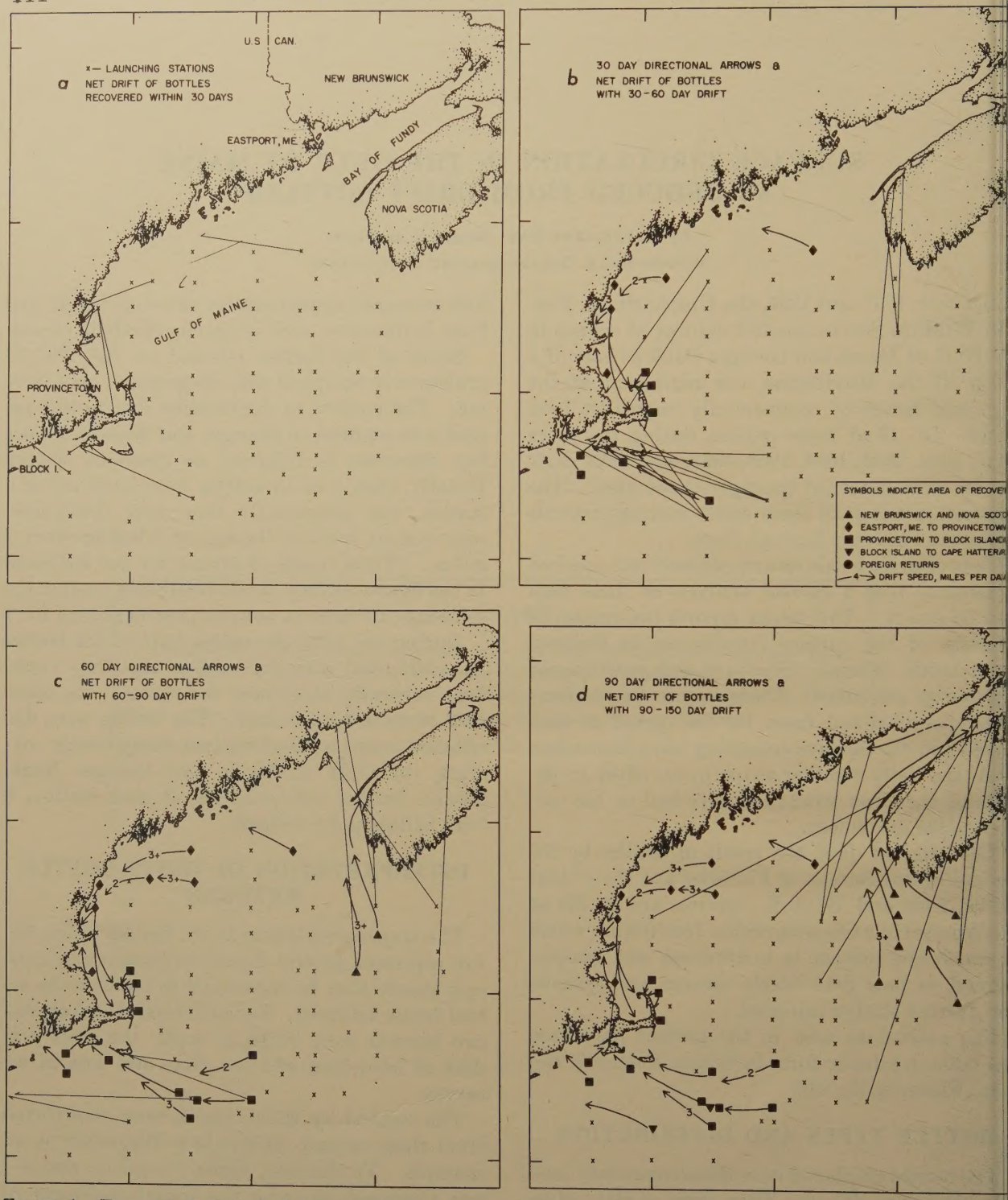

FIGURE 1.—Example of method of interpretation of bottle returns. *a*. Bottles recovered within 30 days of launchin *b*. bottles recovered within 30 to 60 days; *c*. bottles recovered within 60 to 90 days; *d*. bottles recovered within to 150 days. (x indicates station of launching; arrow, direction of drift; figure on arrow, speed of drift.)

is example, enough bottles were found within days of their launching to allow construction this initial picture. It was felt that these early turns, because of time limitations, came closest showing the actual path of drift. They came, course, from the inshore launching stations. hese straight lines were then reduced to the first w directional arrows (fig. 1, *b*), and symbols incating areas of recovery were placed at launchg points.

Similarly, the next group of bottles having rifts of from 30 to 60 days was plotted (fig. 1, *b*), owing straight line or net movement. Again, hese straight lines were reduced to directional arows, drawn to conform as nearly as possible to he first set. This process was repeated for the 60- 90-day drifts which were superimposed as raight lines (fig. 1, *c*). The whole process was epeated (fig. 1, *d*) as often as the data required, ntil all returns had been accounted for.

It will be noticed that in the final chart for ruise 48 (fig. 11), a cyclonic eddy was shown in he northern Gulf of Maine. This was deduced rom the pattern already established (fig. 1, *d*) nd from the fact that some bottles recovered rom these stations had been adrift for more than 00 days, indicating little likelihood of direct ovement toward their recovery point. In addiion, the period of drift for the bottle launched n the north-central part of the eddy exceeded onsiderably the period of drift of those bottles aunched in the southern part, though all were ound in the same recovery area.

In following the method of charting water ovements from bottle recoveries outlined here, ertain general principles have been adhered to. The first-drawn directional arrows, which were ased on relatively few returns, were subject to inor modifications by subsequent, more numerus recoveries. Such changes, never radical in ature, seldom had to be made, however. Very ate returns, which came in after many months or ven years, were arbitrarily made to fit the previusly established pattern.

Where a concentration of release stations appeared from which there were no returns, directional arrows were made to avoid this area, which was assumed to be characterized by an offshore movement. (Note the northward confinement of the Gulf eddy in figure 11.) Where alternate routes appeared possible, the one more consistent in terms of drift velocity was chosen. Where velocities have been entered, they indicate the fastest drift as being most representative, since other slower bottles may have lain undiscovered on the beach for some time. Where routes were most open to question, a dashed line was used in plotting.

Finally, it should be stated that the plots were completed before the surface wind vectors were read from daily weather maps and graphed. Thus, knowledge of wind patterns in no way influenced the assumed course of bottles.

The end result of this treatment is seen in the charts for each cruise. In referring to them it should be remembered that—

1. Arrows show directional trends, not actual routes followed.

2. A single arrow may show the trend of a number of bottles.

3. Symbols—used in figures 3 to 19—at the point of release (near the base of an arrow) indicate the general region of ultimate recovery.

4. Positions of all stations at which bottles were dropped are shown with the exception of a few instances during the 1931–34 cruises where bottles were set out in short lines of 2 bottles every 2 miles. In some instances where bottles from the same launching position stranded in different recovery areas, two or more symbols are grouped together.

For purposes of comparison, the 17 cruises considered here have been divided on a seasonal basis into five groups (table 1): Group *A*, late February and early March; group *B*, late March and early April; group *C*, late April and early May; group *D*, late May and early June; and group *E*, late June.

Each cruise is considered from the following aspects:

1. How does it agree or disagree with other cruises in the same seasonal category?

2. Are there any seasonal circulatory characteristics?

TABLE 1.—*Summary of drift-bottle releases in the Gulf of Maine, by cruise and year*

Cruise	Date	Number released	Number returned [1]	Percentage recovered
Group *A:*				
Albatross III:				
Cruise 57	Feb. 21–Mar. 2, 1955	648	34	5.2
Cruise 71	Feb. 20–Mar. 2, 1956	719	54	7.5
Group *B:*				
Albatross III:				
Cruise 46	Mar. 19–Apr. 2, 1953	801	58	7.2
Cruise 58	Mar. 19–Apr. 1, 1955	826	76	9.2
Cruise 72	Mar. 21–31, 1956	633	47	7.4
Albatross II	Apr. 4–18, 1932	737	77	10.4
Group *C:*				
Albatross II	Apr. 17–29, 1931	450	49	10.9
Atlantis: Cruise 28	Apr. 27–May 13, 1934	629	101	16.1
Albatross III:				
Cruise 48	Apr. 24–May 8, 1953	970	108	11.1
Cruise 60	Apr. 19–May 3, 1955	1,235	139	11.3
Cruise 73	Apr. 17–28, 1956	780	72	9.2
Group *D:*				
Albatross II	May 26–June 7, 1931	352	58	16.5
Albatross III:				
Cruise 50	May 25–June 2, 1953	552	39	7.1
Cruise 61	May 16–28, 1955	672	77	11.5
Cruise 75	May 16–29, 1956	1,078	119	11.0
Group *E:*				
Atlantis: Cruise 16	June 19–28, 1933	532	93	17.5
Albatross III: Cruise 76	June 11–24, 1956	1,137	90	7.9
Total		12,751	1,290	

[1] As of December 1956.

3. To what extent can differences or similarities be accounted for by the wind patterns during and immediately following each cruise?

4. How does it agree with or depart from Bigelow's (1927, fig. 207) schematic diagram of the circulation in this area?

Although figure 2, based on Bigelow's diagram of nontidal circulation is for July and August, it is used throughout this discussion as a convenient norm for comparison with each of the cruises.

Bigelow summarized the circulation in the Gulf of Maine as a general anticlockwise eddy around the basin of the Gulf. He called this the "Maine" or "Gulf of Maine" eddy. We have called it the "Gulf" eddy. He pointed out (p. 972) that—

> The eddying drift is operative throughout the year, but differs in velocity and generally in detail, from season to season. It is also complicated by subsidiary eddying movements in the Bay of Fundy, Massachusetts Bay, Vineyard Sound, around Nantucket and Nantucket Shoals, and around and over Georges Bank, which are clockwise around these shoals but counterclockwise in the bays and basins * * *.

We shall call the clockwise eddy around Georges Shoals the "Georges" eddy.

For convenience, reference is made in the discussion of cruises, which follows, to four arbitrarily defined areas within the region of study. These are superimposed on Bigelow's schematic diagram as well as on the subsequent plots.

SURFACE CIRCULATION PATTERNS IN THE GULF OF MAINE

GROUP *A* CRUISES: LATE FEBRUARY AND EARLY MARCH

Albatross III cruise 57, February 21–March 2, 1955 (Figure 3)

In area I, there is a pronounced southerly mov ment along the western shore of the Gulf and the are indications of a strong seaward movement ea of Cape Cod through South Channel, breaking t southwestern sector of the Gulf eddy. Maximu velocities are in the order of 2 miles a day. Wat movement in area II differs from Bigelow's di gram in that the northward flow from Brow Bank into the Bay of Fundy is not clearly esta lished, two stations showing movement to sout eastern Nova Scotia and one station showing 540-day drift to Maine. Area III shows the retu of 1 bottle out of 84 bottles put out at 7 statio (12 per station). At other times, returns wou have been had from Long Island and the sout west as far as Cape Hatteras.

The best agreement with Bigelow, though t data are scarce, is found in area IV. On t northern edge of the Bank, the Gulf eddy is ind cated by 3 returns from 1 station; 1 bottle entere the Bay of Fundy and 2 reached the western sho of the Gulf. Anticyclonic movement arou Georges Bank is suggested by westward drift fro two stations and pronounced seaward moveme from the eastern and southern edges by the co centration of no-return stations and the scattere foreign returns.

The apparent resultant of wind vectors for 4 days following the cruise shows a dominant wi from about west-northwest. Whether one assume a movement of surface water to the right of t wind in accordance with Ekman (1902) or a dire downwind transport, winds could well account f the departures from the norm, as taken fro Bigelow.

Albatross III cruise 71, February 20–March 2, 1956 (Figure 4)

Area I, for this period, is in close agreeme with area I, cruise 57, of 1955, in the pronounce southward movement of bottles toward Cape Co and the lack of bottles returning via the Gulf edd to northern and eastern waters. Velocities a

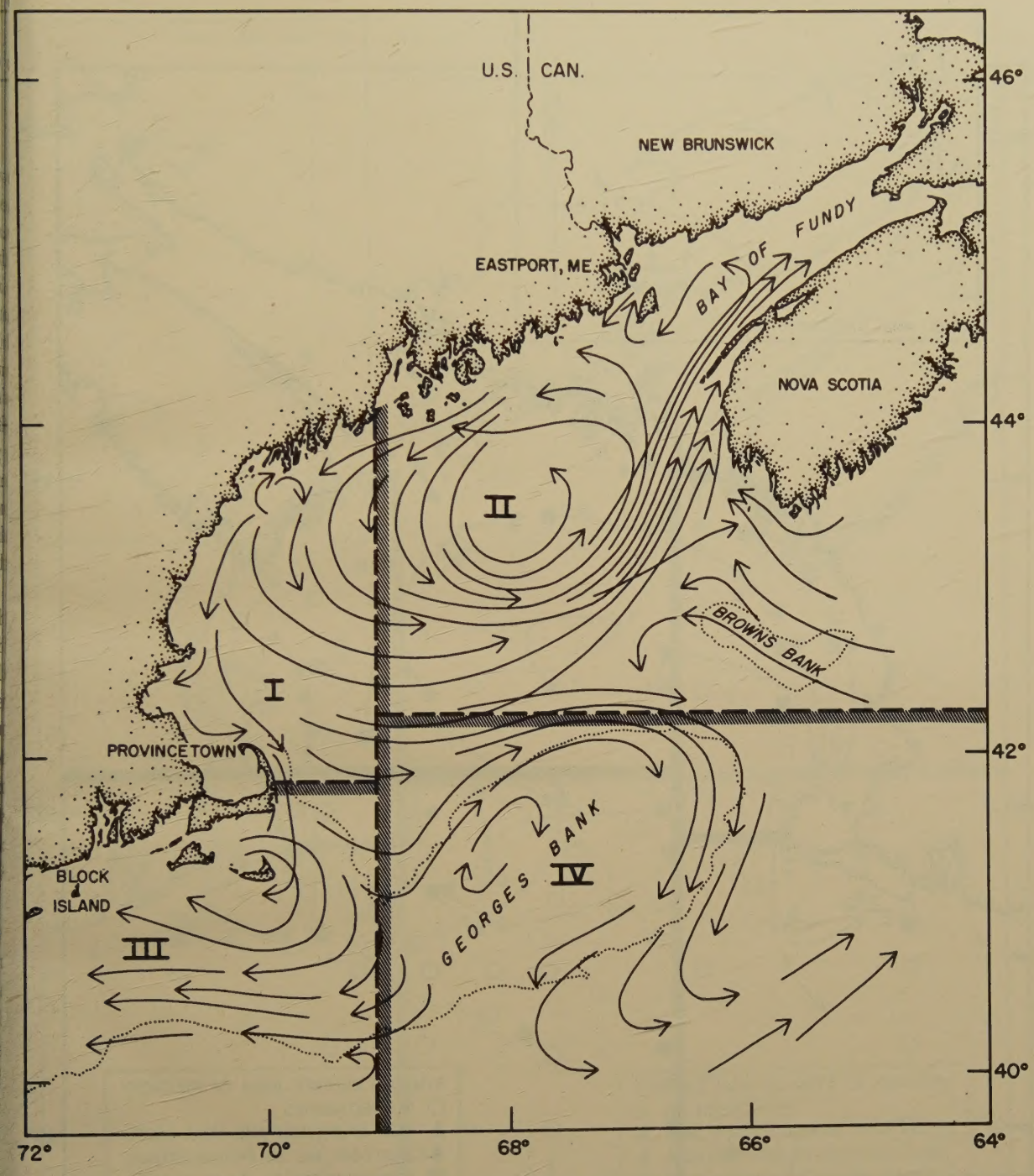

FIGURE 2.—Orientation chart based on Bigelow's diagram of water circulation during July and August in the Gulf of Maine.

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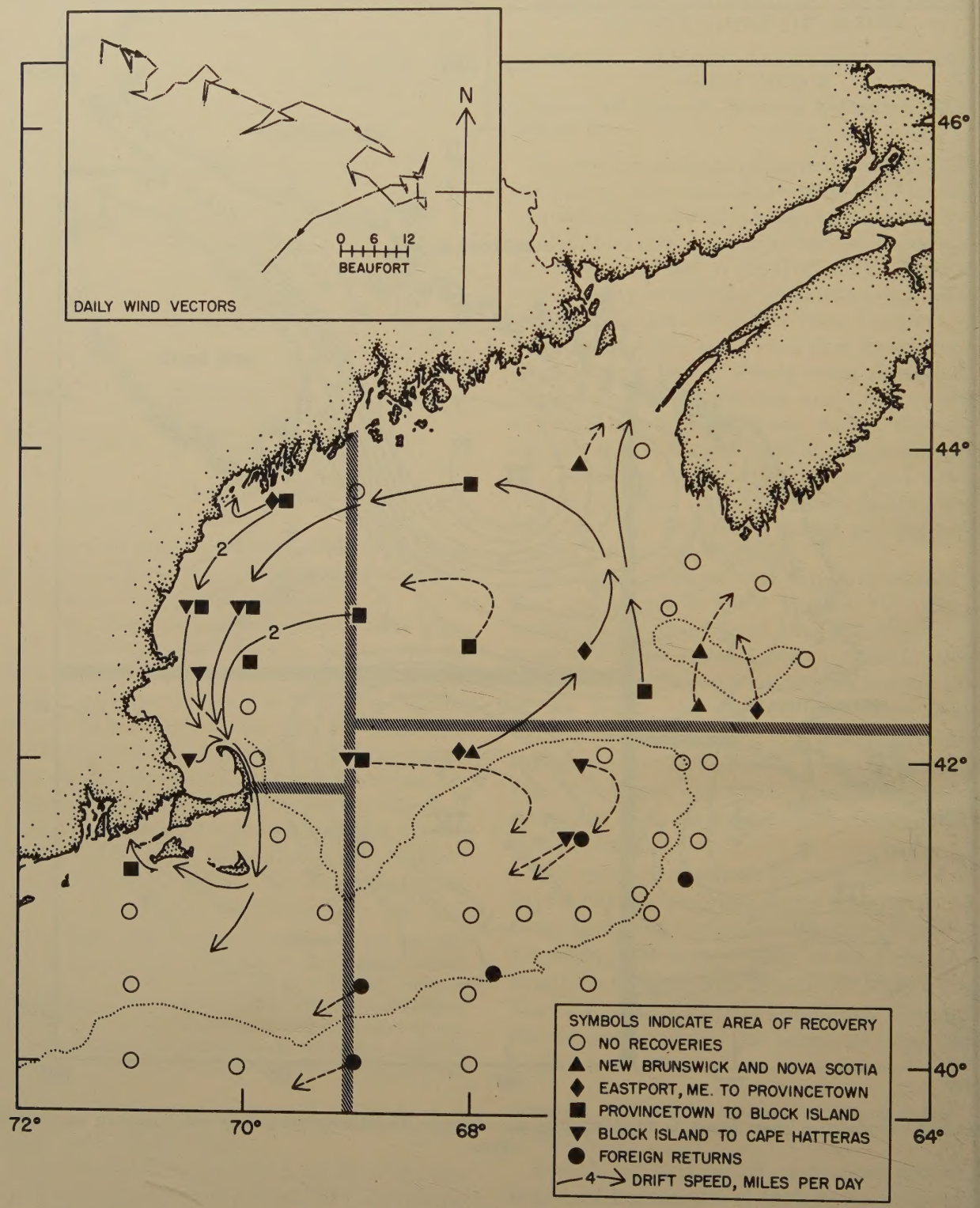

FIGURE 3.—Surface circulation in the Gulf of Maine as deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 57, February 21–March 2, 1955.

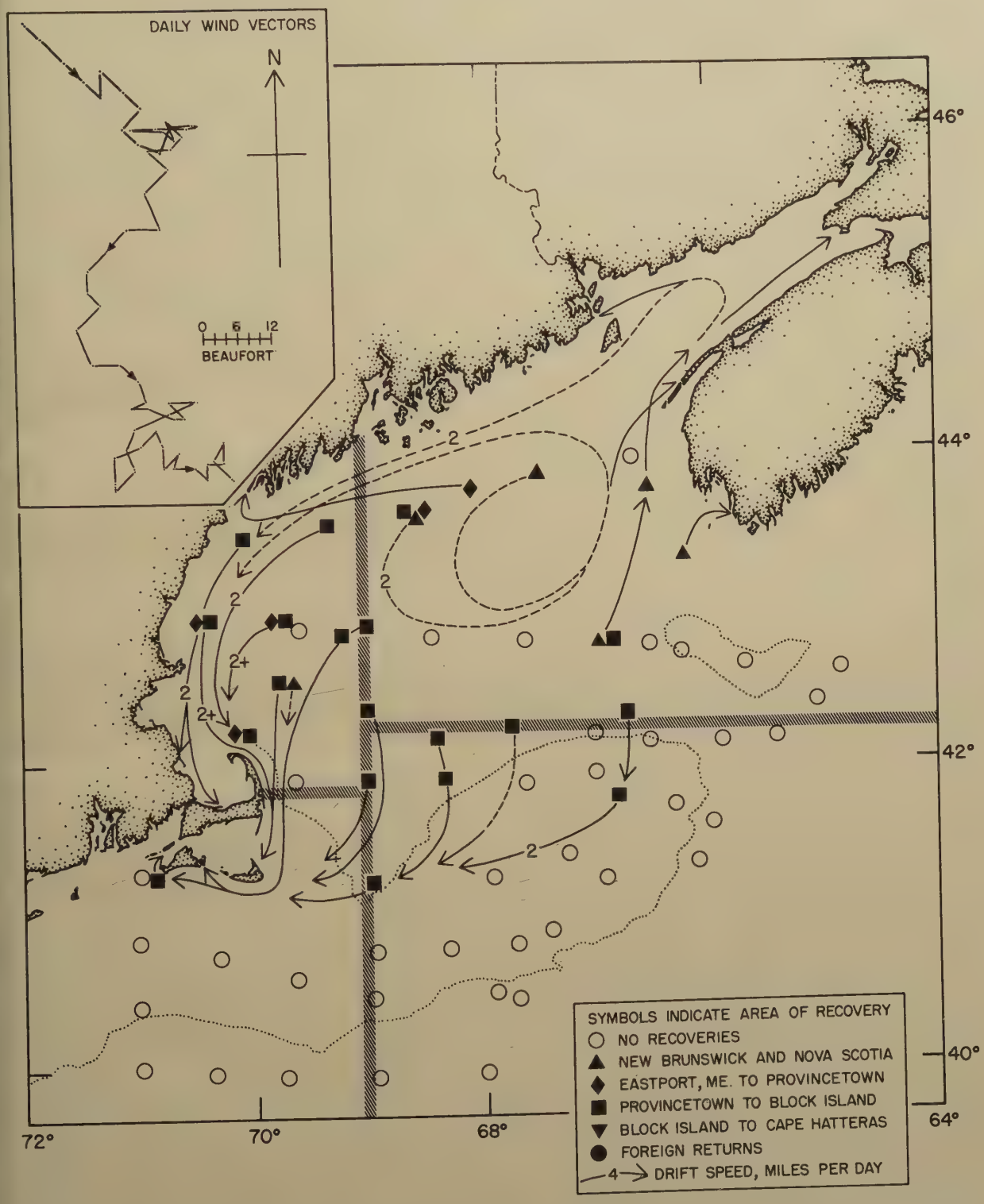

FIGURE 4.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 71, February 20–March 2, 1956.

comparable though slightly in excess of those for 1955.

In area II, three salient features appear: The Gulf eddy has been confined to the northeast; there are no returns from the Browns Bank region and the northward flow toward the bay of Fundy is singularly weak and displaced westward; and there appears no flow from northern Georges Bank toward the Bay of Fundy. The movement here is sharply toward Cape Cod and the islands.

Conditions in area III are very like those of a year earlier. Only one out of nine stations has been heard from to date, this one being close to Gay Head. No bottles have been picked up to the westward, contrary to the pattern of later seasons.

Area IV shows conditions during cruise 71 that are unique among our 17 cruises. All signs point to strong southerly movement normal to the usual easterly flow at the confluence of the Gulf and Georges eddies, along the north edge of the Bank. As was the case in cruise 57, no local United States returns have been had from stations south of 41°N. latitude.

The wind vectors following this cruise show 10 days of winds from different quarters, essentially canceling each other, and then a period of northerlies of more than usual force for 20 days. This latter period, it appears, could well account for all the features described in the four areas. That the surface waters were wind influenced is apparent from a comparison of the first and last stations for the cruise, which were made to the southwest of Gay Head. There were no returns from station 1, which was followed by 11 days of northwesterlies; there were four returns from Vineyard Sound from station 60, which was followed by 10 days of mutually negating winds.

If one may make generalizations on the basis of two cruises, it may be said that when winds from the northwest quarter prevail during late February and early March, the idealized circulation in the region will be modified thus:

1. Surface waters from the western Gulf will tend to flow southward past Cape Cod and out South Channel, thus interrupting the Gulf eddy in this area and tending to confine it to the north and east.

2. The northward movement from Browns Bank into the Bay of Fundy will be greatly diminished, some water being deflected along the southeastern coast of Nova Scotia.

3. The usual westward movement of water south of Nantucket and Martha's Vineyard will be deflected offshore or temporarily interrupted.

4. The Georges eddy will be ill-defined and tend to disappear as winds become more northerly.

Under these conditions, the survival chances for eggs or larvae are small, unless confined to the northeastern sector of the Gulf.

GROUP *B* CRUISES: LATE MARCH AND EARLY APRIL

Albatross III cruise 46, March 19–April 2, 1953 (Figure 5)

A southerly movement of 4 miles per day generally parallel to the coast characterizes the waters in area I for this period. There is no indication from drifts for this cruise that the Gulf eddy is yet established, as there appears to be no return flow from this region to the northeast.

The northward flow from Browns Bank and the tip of Georges Bank in area II is firmly established, as is the veering to the northwest toward the coast of Maine, thus completing the eastern and northern segments of the eddy. Velocities up to 4 miles a day agree with those in area I. The picture agrees well with that of Bigelow, except in the southwestern part of the area.

The westerly drift south of Cape Cod and the islands is established in area III. Three unballasted bottles launched just east of the Cape moved northwest at 5 miles a day, driven by 5 days of wind from the southeast and east. The expected movement here is southerly.

Only three drift-bottle returns were had from Georges Bank in area IV. Two of these bottles moved westward to Long Island and Oregon Inlet at better than 2 miles a day. The third probably followed the path suggested by Bigelow, veered off the southern edge of the Banks and traveled at nearly 4 miles a day to the neighborhood of Sable Island.

The pattern of no-return stations for this cruise suggests an outflow from the Gulf across eastern Georges Bank, breaking the southern segment of the Gulf eddy. It is unusual to have a concentration of no-return stations occur so far to the north in the Gulf as it did on this cruise.

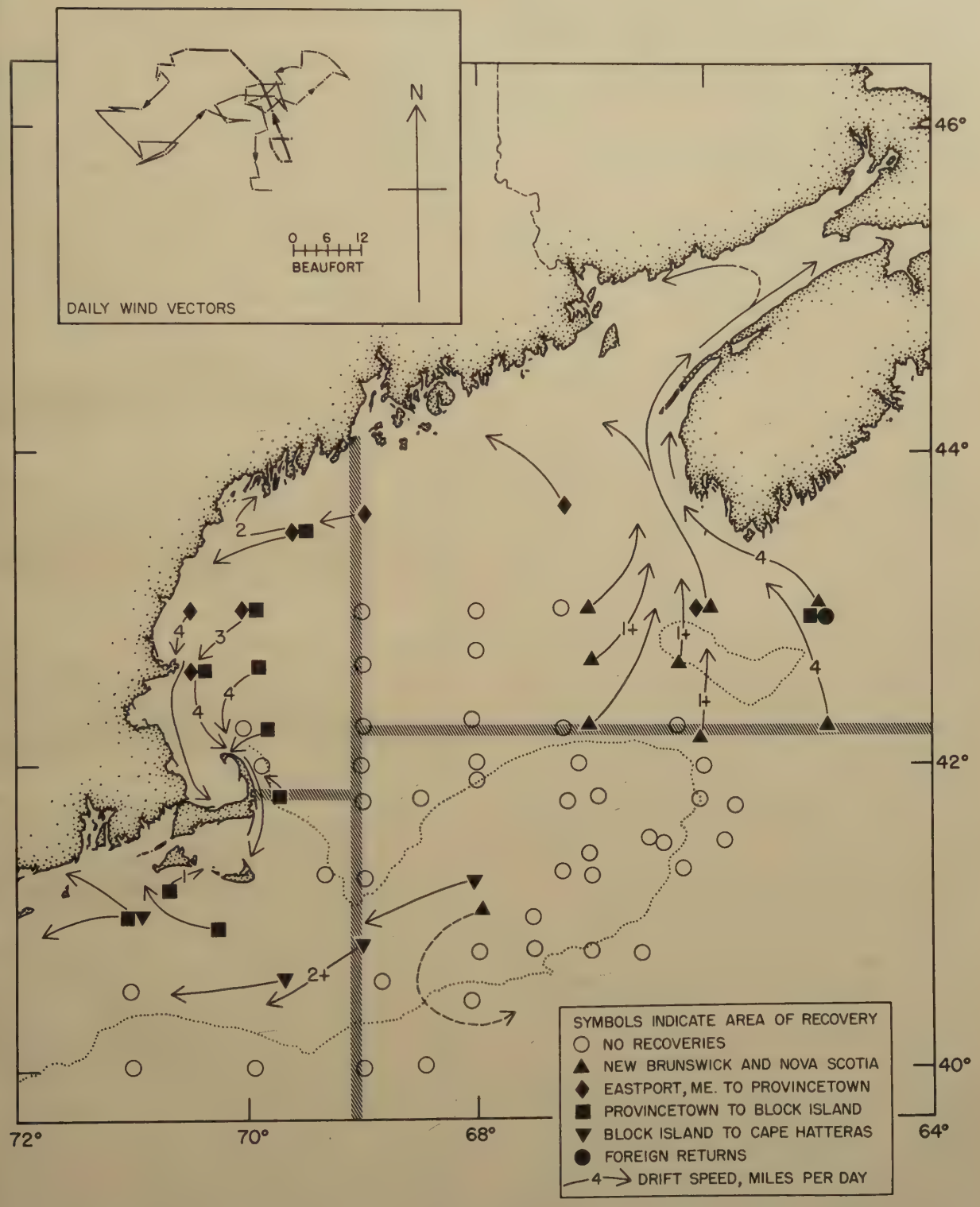

FIGURE 5.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 46, March 19–April 2, 1953.

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It is not possible to see any wind influence during this cruise except on the very short drifts we have mentioned. Wind vectors for the 60 days following the last bottle drop tend to counteract one another.

***Albatross III* cruise 58, March 19–April 1, 1955 (Figure 6)**

The net drift in area I during this period is southerly, but there appears to be a strong westward, onshore component with no sign of an eastward return of the Gulf eddy.

Circulation in area II is in general agreement with that described by Bigelow for this area, except that the southern segment of the Gulf eddy is broken.

Of 120 bottles launched in area III, only two returns were had, they being from Maryland and Virginia. This agrees with the large number of bottles from north of Cape Cod and from Georges Bank which ultimately stranded to the west.

A good number of drift-bottle returns were had from Georges Bank, all showing a southwest movement but giving little indication of an anticyclonic eddy around the Bank.

The wind vectors show the first directional dominance to be northeasterly beginning 20 days after the end of the cruise, when there were 5 consecutive days of force-5 winds from this quarter. There is little doubt that winds of this force and duration influenced surface movement, but whether they alone produced the southwesterly movement which characterizes this group of bottles cannot be stated.

***Albatross III* cruise 72, March 21–31, 1956 (Figure 7)**

Unfortunately, this cruise did not cover the northern part of the Gulf of Maine; as a result, little can be deduced about the state of the Gulf eddy at this time.

Only three bottle-drop stations were made in area I. Of the total of 36 bottles put out, 2 were recovered in area III some months later.

Area II shows surface water movement of better than 2 miles a day from western Browns Bank north into the Bay of Fundy. Stations east of Browns Bank were not heard from.

There were good returns from offshore stations in area III, which show a pronounced northerly component to the usual westward flow expected here.

Returns from Georges Bank (area IV) indicate a southwest movement, probably becoming more westerly somewhere in the vicinity of South Channel. There are no returns to indicate the existence of the Georges eddy. The tendency for bottles to move westward beyond Block Island, as in the previous cruise, is not seen here.

Vectors show winds to be more directional for this cruise than for the two other cruises in group *B*. There was a slight northwesterly set during the first 38 days following the last bottle-drop station. This gave way to southwesterlies which predominated for the next 30 days and so markedly influenced the results of the succeeding cruise (cruise 73, fig. 13). Comparison of cruises 72 and 73 indicate that the critical winds occur during the first month following a cruise. Thus, to estimate loss or survival of fish eggs and larvae, accurate knowledge as to dates and location of the heaviest spawning is essential.

The three cruises of group *B*, which cover the last 10 days of March for 3 different years, have these points in common.

1. The Gulf eddy is complete on the eastern, northern, and western segments in 1953 and 1955 (cruises 46 and 58), but appears broken on the southern segment, the movement here being either offshore or southwesterly across Georges Bank and out of the Gulf.

2. The northern sector of the Georges eddy, where it sometimes becomes confluent with the Gulf eddy, is not apparent. The surface-water movement is southwesterly across the Bank.

3. The generally westward movement south of Cape Cod and the islands appears established.

4. It would appear that surface plankton in the central and western Gulf of Maine or over Georges Bank would have been carried out of the region in a southwesterly direction in 1955 and 1956 and possibly offshore in 1953.

INTERMEDIATE CRUISE

***Albatross II* cruise, April 4–18, 1932 (Figure 8)**

This cruise is intermediate, seasonally speaking, between groups *B* and *C*, and is treated separately. Bottles were seeded only over the south-

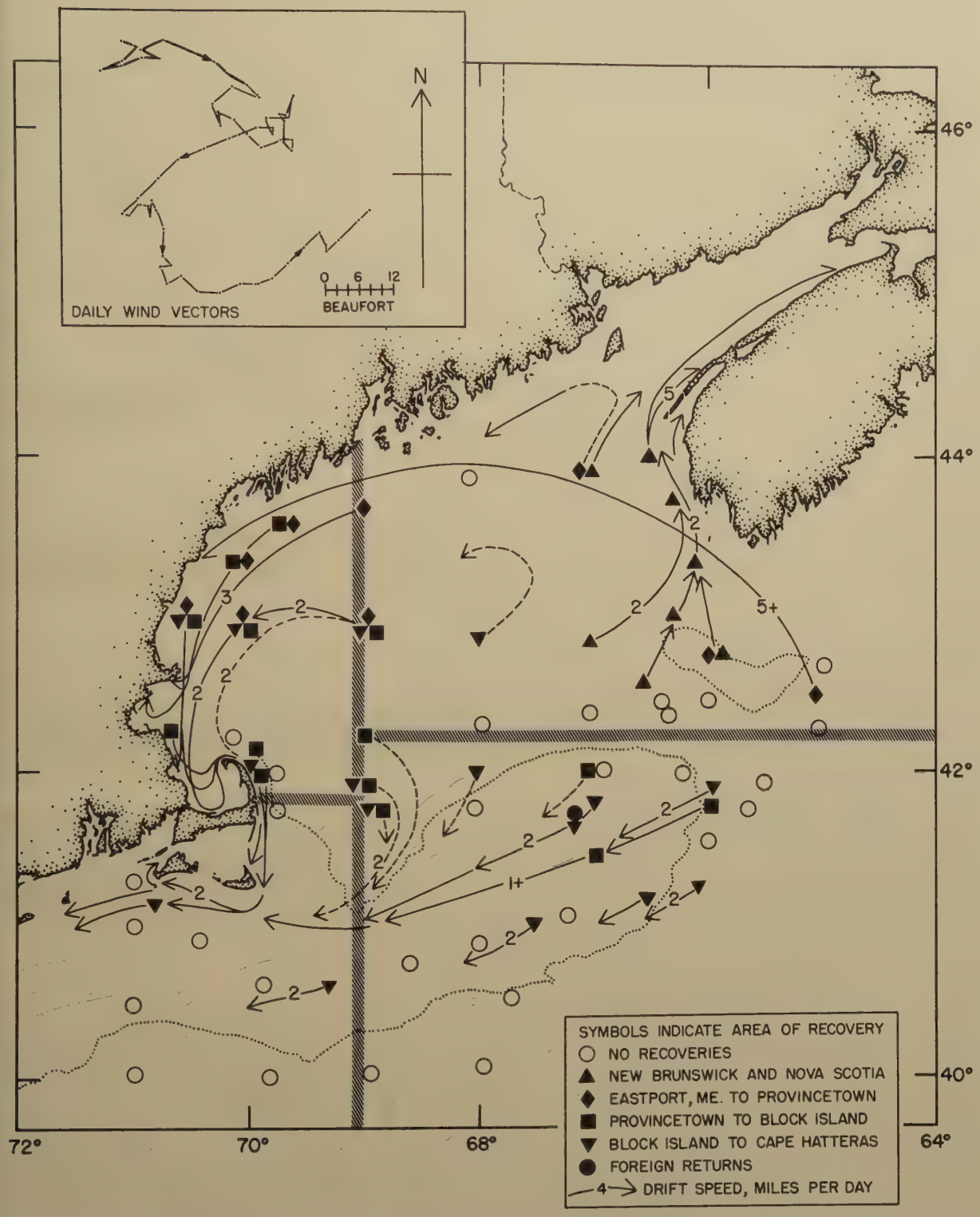

FIGURE 6.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 58, March 19–April 1, 1955.

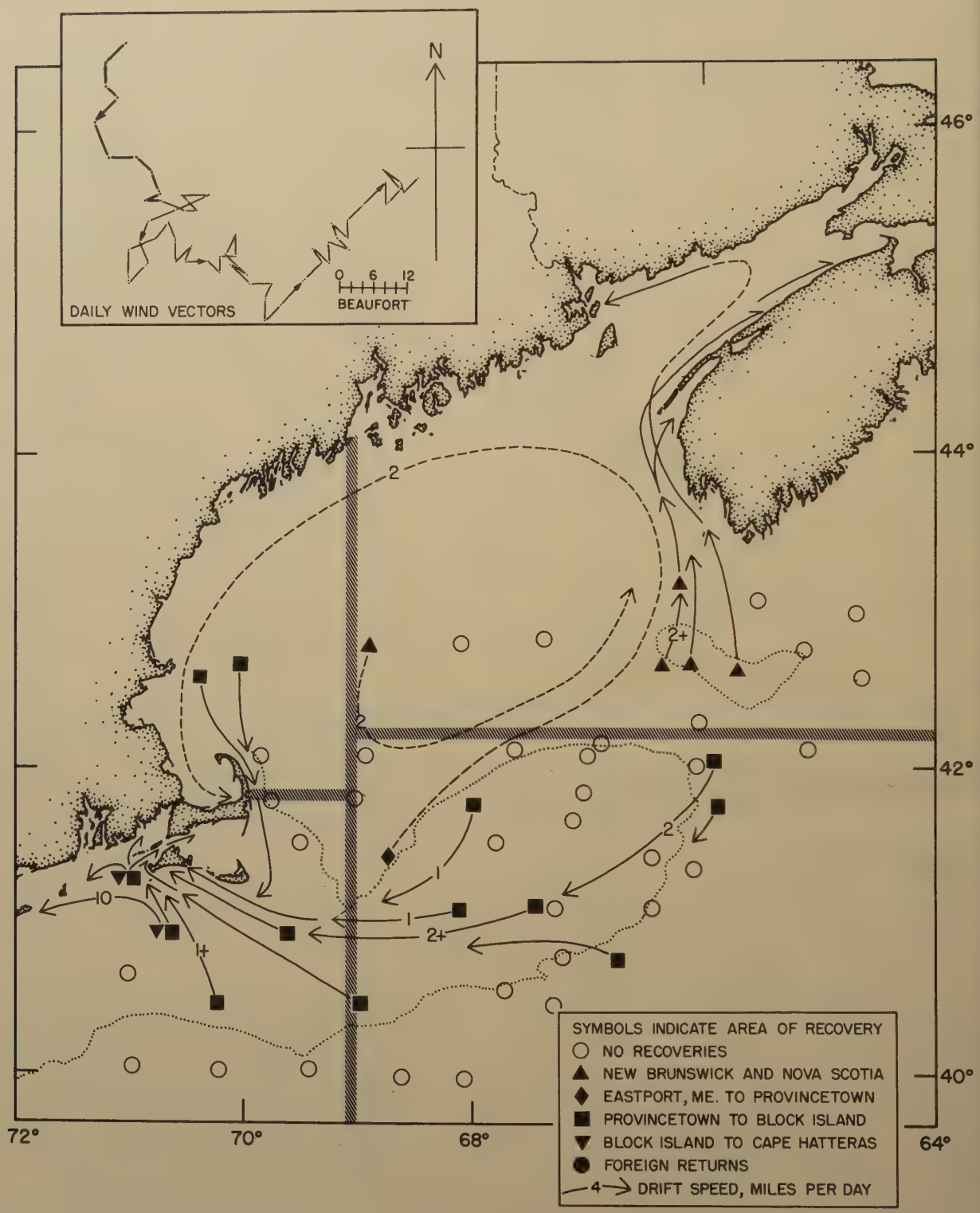

FIGURE 7.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 72, March 21–31, 1956.

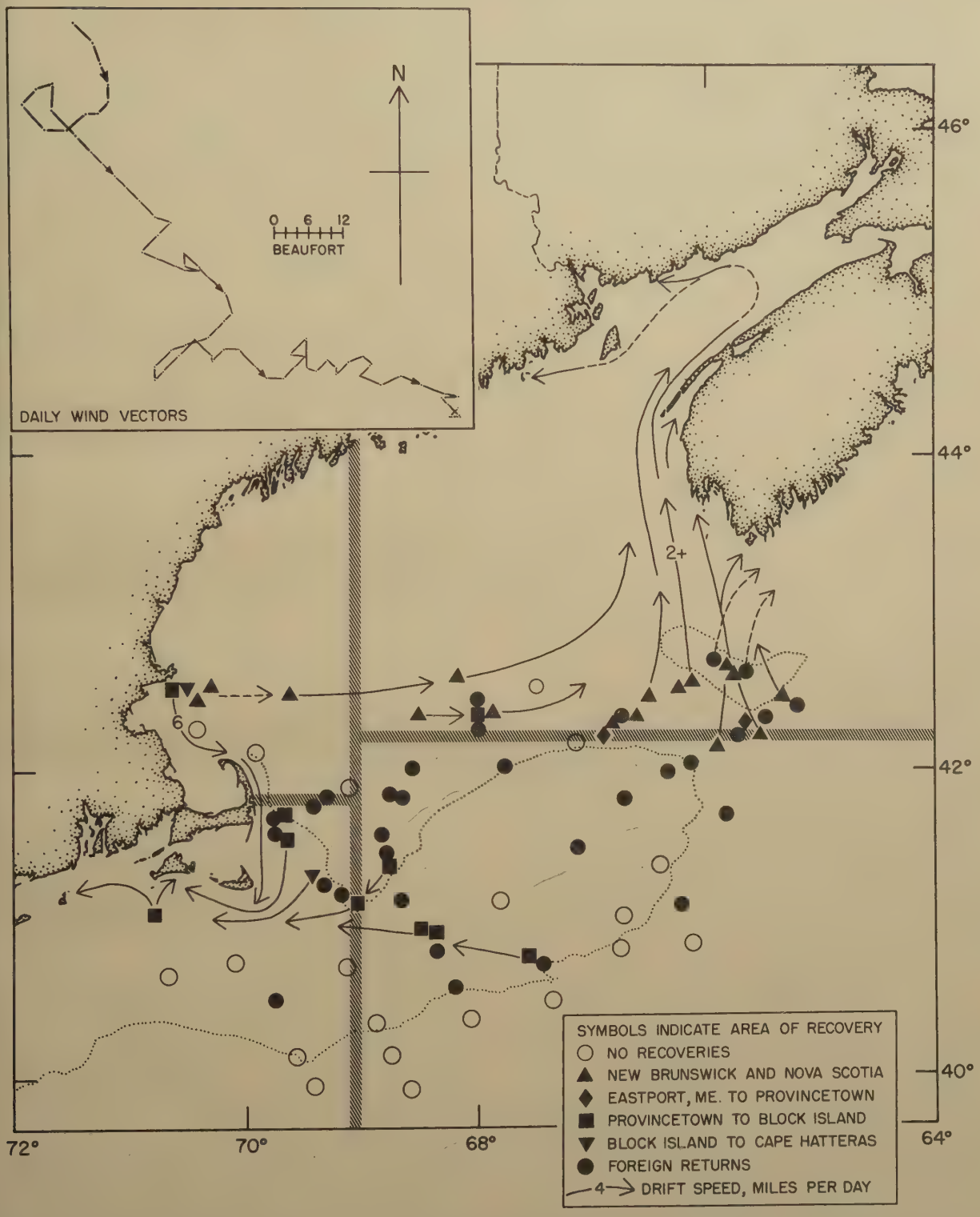

FIGURE 8.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross II*, April 4–18, 1932.

ern part of our region of study, but certain characteristics are well defined.

For the first time, seasonally speaking, the southern segment of the Gulf eddy appears clearly, with bottles seeded north of Cape Cod returning to Canadian waters. The northward movement from Browns Bank toward the Bay of Fundy is apparent.

From Georges Bank and South Channel, there is a preponderance of returns from abroad with little indication of the initial route followed by the bottles. Whether the bottles first started toward the west or traveled downwind in a southeasterly direction, it is apparent that the surface-water movement was away from the region of study. As there were more returns than normal from Newfoundland, Sable Island, and eastern Nova Scotia, and fewer than usual from Long Island, it would seem reasonable to assume that the bottles followed a downwind course in moving out of the region.

In discussing the circulation deduced from the *Albatross II* cruises (figs. 8 and 9), Walford (1938, p. 49) states: "It is evident * * * that there was a very important difference between the circulatory picture in the season of 1932 and that of the corresponding period of 1931."

Inspection of the wind vectors for these cruises appears to indicate wherein the difference lies. In 1931 they show little directional dominance, while in 1932 the offshore tendency is clearcut. That winds are often responsible for anomalies in circulation in this region cannot be denied. Better understanding is needed of how winds from different quarters may establish or modify the circulation of water depending on their force and duration.

GROUP *C* CRUISES: LATE APRIL AND EARLY MAY

Albatross II cruise, April 17–29, 1931 (Figure 9)

This cruise, confined to Georges Bank, covers areas III and IV only. The drift-bottle returns, however, indicate that the southern segment of the Gulf eddy has appeared, joining the northward-moving water over Browns Bank.

Area III shows a strong northerly set which is eventually deflected westward closer to land. This movement agrees with the clockwise eddy which is now firmly established around Georges Bank at a minimum rate of 2 miles a day. The six foreign returns were from stations along the southern edge of the Bank; they could have veered southward from the eddy in the manner suggested by Bigelow or have moved southwest toward Cape Hatteras and there entered the Gulf Stream.

Winds for 30 days following the cruise show that they probably had little effect on the surface-water movement.

Atlantis cruise 28, April 27–May 13, 1934 (Figure 10)

This cruise, also limited to the south and east, nevertheless shows the Gulf eddy as established in these areas, and it seems reasonable to assume that it was complete on the northern and western sectors as well. From Browns Bank, some bottles tended eastward and some into the Bay of Fundy, a situation which may reflect the conflicting winds which characterize the 50-day period following the cruise.

The surface movement in area III is southward out South Channel and thence westward, with none of the northerly motion noticeable in the preceding cruise. Only 1 of the 101 returns came from the Nantucket-Martha's Vineyard area, while many came ashore on Long Island and points west.

The Georges eddy in area IV is quite apparent at this time, as is the southern segment of the Gulf eddy where the two seem to meet north of the Bank. A surprising aspect is the fact that 36 of the 101 bottle returns came from overseas; stranding points were widely distributed between Norway and the Bahamas. There is nothing in the wind pattern to explain this offshore tendency. In view of the large number of recoveries between Long Island and Cape Hatteras, it may well be that the "foreign" bottles initially moved in this direction before entering the Gulf Stream near Cape Hatteras.

Albatross III cruise 48, April 24–May 8, 1953 (Figure 11)

The drift pattern in area I agrees well with Bigelow, except that the return flow of the Gulf eddy does not extend as far south as he shows it. Southward velocities along the coast are 3 miles a day.

Water movement in area II agrees almost exactly with Bigelow, as does that in area III.

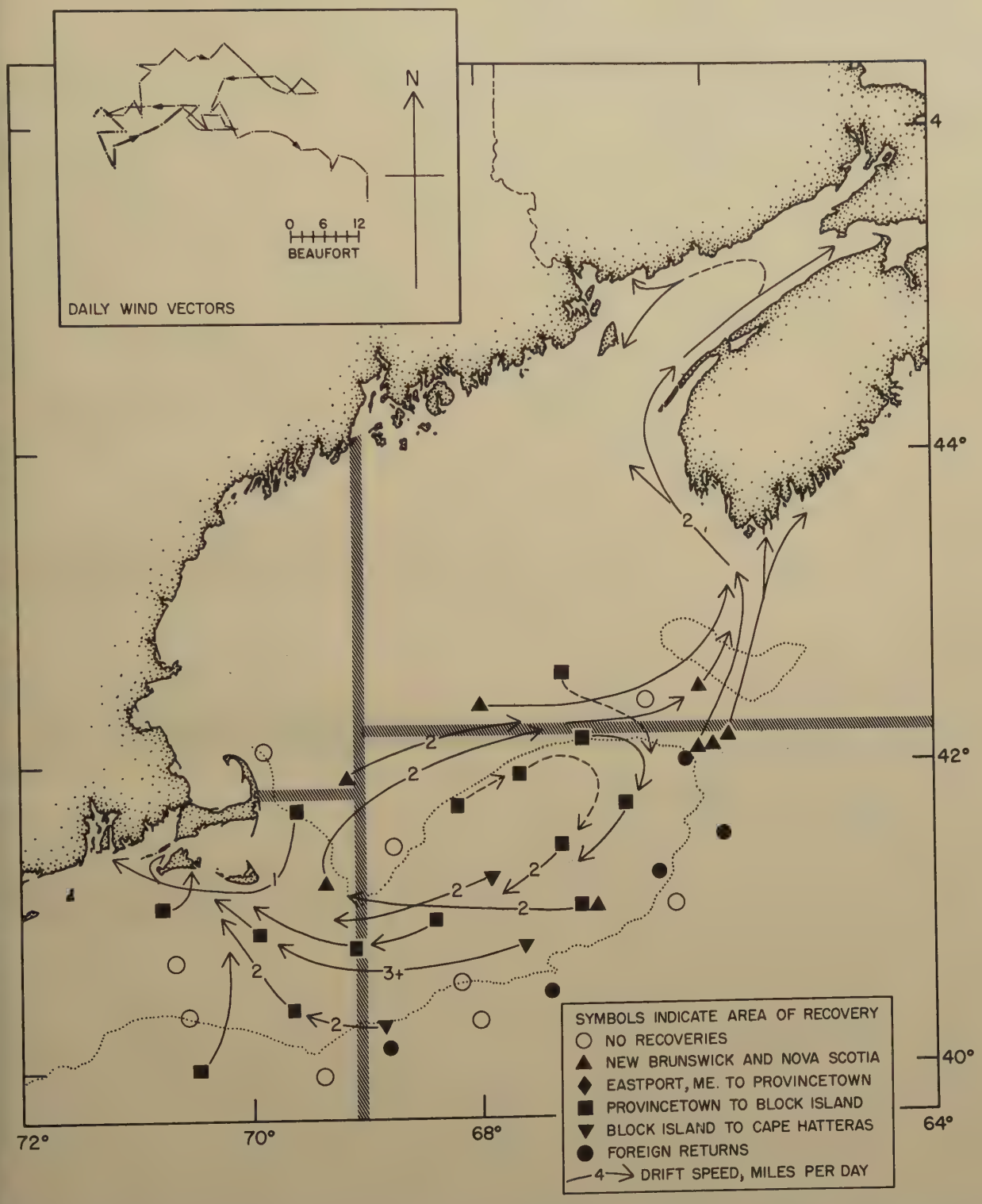

FIGURE 9.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross II*, April 17–29, 1931.

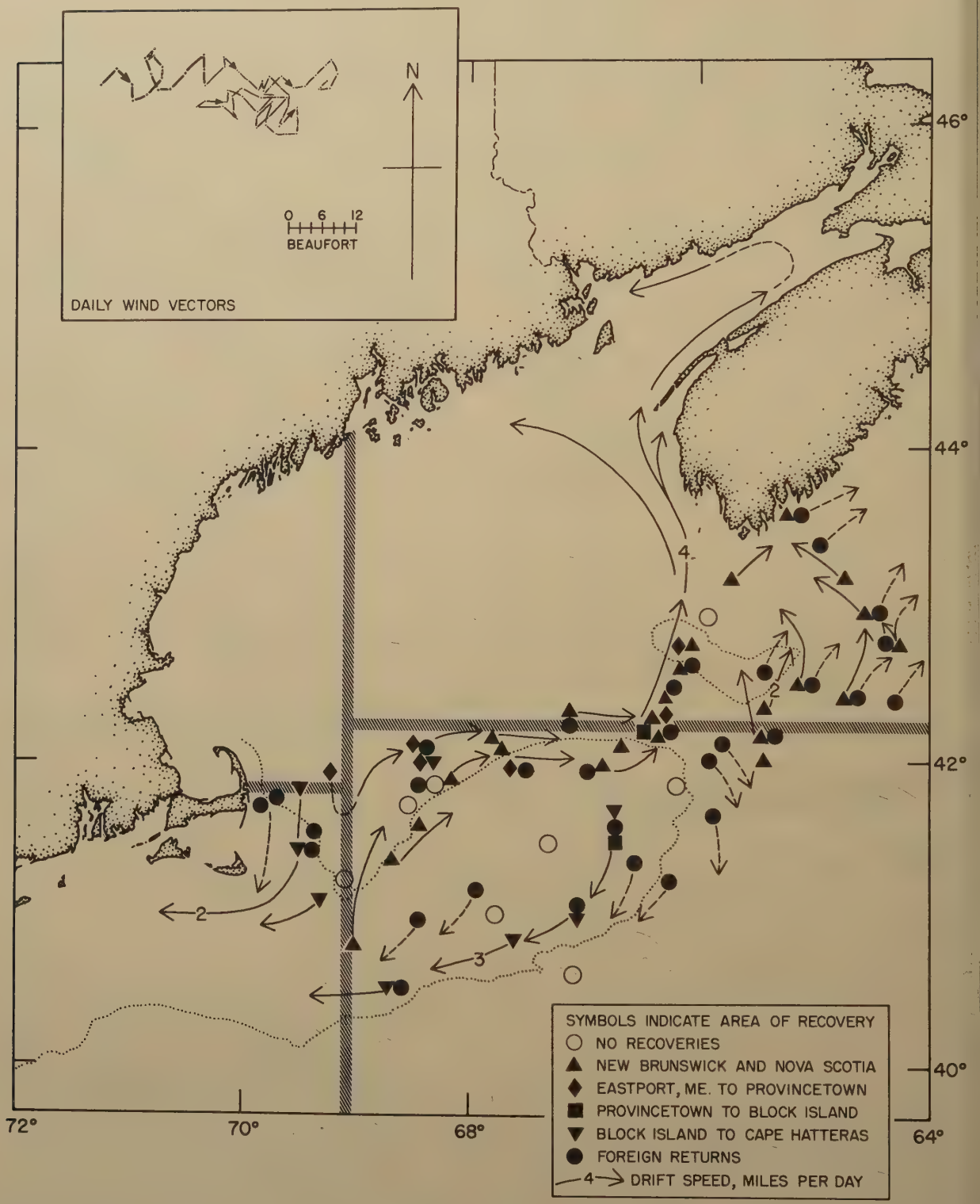

FIGURE 10.—Surface circulation deduced from recoveries of drift bottles launched by *Atlantis*, on cruise 28, April 27–May 13, 1934.

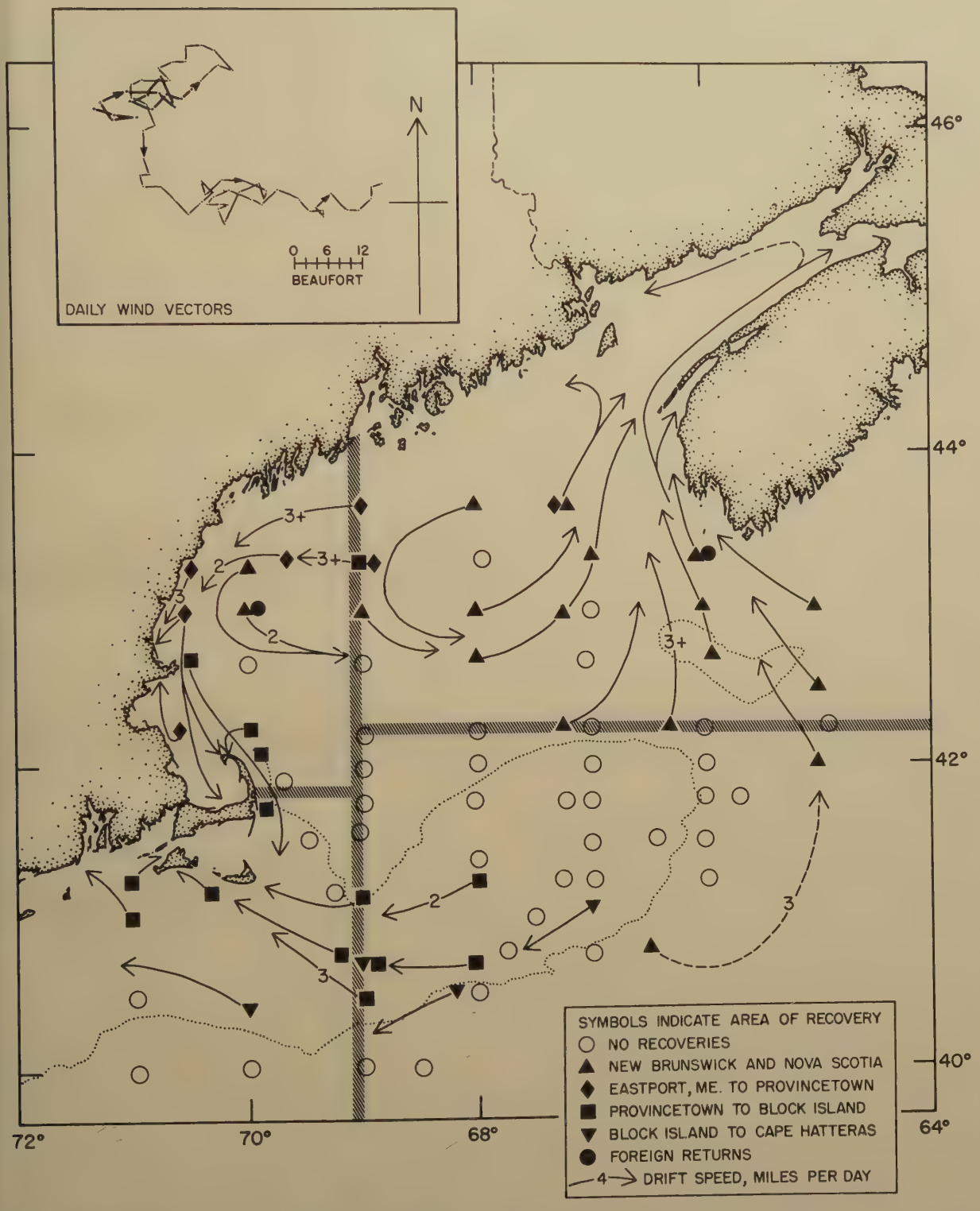

FIGURE 11.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 48. April 24–May 8, 1953.

Though bottle returns from area IV indicate no Georges eddy, the number of no-return stations in the southern Gulf and northern edge of the Bank can reasonably be assumed to show a general eastward movement through the region with a pronounced outflow off eastern Georges Bank. If this were the case, then the circulation could be said to agree very well with Bigelow's diagram.

All told, this cruise in late April and early May of 1953 is the first to agree with Bigelow in all four areas.

***Albatross III* cruise 60, April 19–May 3, 1955 (Figure 12)**

There were 21 drift-bottle returns from the five stations north of Cape Ann in area I, which show the occurrence of unusual velocities of from 8 to 12 miles a day. Thirteen of these bottles (three with and ten without ballast) came ashore before the end of the cruise on May 4 and very obviously owe their high speeds to a fair wind augmenting the usual southwesterly movement (see vectors, fig. 12). In the southern part of the area, the same winds undoubtedly account for the pronounced water movement out South Channel with no indication of easterly flow in the Gulf eddy.

The cyclonic movement around Browns Bank in area II was drawn because it best fits the wind pattern and logically explains the no-return stations immediately to the northwest. The Gulf eddy is firm on the east and north.

Surface water in area III shows marked movement out South Channel. It is to be noted that there were no local returns from stations made at the start of the cruise in the region south of the islands when winds were northeasterly for some days; but four stations in this area were heard from locally at the end of the voyage, during a time that was characterized by calms and light westerlies. Thus, wind influence on the bottles released in this area may be called "marked."

The Georges eddy on the north is confirmed by one return from the Bay of Fundy with a second possibly making the circuit before going to the west. There were many returns from southern Georges Bank, which fit well with the northwesterly movement seen in area III during this period.

As has been noted previously, the wind pattern, which is relatively clear-cut during and after the cruise, could be said to have had a marked influence on the drift of bottles released at this time.

***Albatross III* cruise 73, April 17–28, 1956 (Figure 13)**

To date, there are only 7 returns from the 84 bottles put out at 7 stations in area I during this cruise. The difference here between this cruise and the other cruises in group *C* is marked and can only be attributed to the winds prevailing at this time. With the exception of two bottles coming into the area from the east, little or no southerly movement of surface water is indicated. That there were no returns from the station immediately south of Cape Ann can only be explained by the winds.

The northward movement of water into the Bay of Fundy appears displaced slightly to the west, with velocities of 4 miles a day. The one return from south of Browns Bank shows a net movement of 75 miles in 95 days, which tells little. The northeasterly motion along the Nova Scotian side of the Bay of Fundy is accelerated to 6 miles a day.

Area III shows no southerly movement of bottles through South Channel, while south of the islands the usual westward flow is strongly deflected shoreward. The appearance and progression of this northerly deflection are apparent in the sequence of the five cruises in 1956, the deflection becoming more pronounced as the season advanced.

Two returns only were had from the entire Georges Bank region: one at Gay Head and the other in Buzzards Bay. It is hard to believe that these returns represent the dominant movement from the Bank, in view of the many no-return stations which surround the two points of release.

The first three cruises discussed under group *C* have wind patterns showing no very clear directional dominance. Thus it would appear possible to consider the deduced surface movement in these years to be fairly typical for the season. The cruises themselves agree reasonably well, and show, in general, that the idealized surface circulation as seen by Bigelow is taking shape for the first time, seasonably speaking. All three cruises show the Gulf eddy to be completed in its southern sector, a condition not noticeable in earlier cruises. The Georges eddy was clearly present in

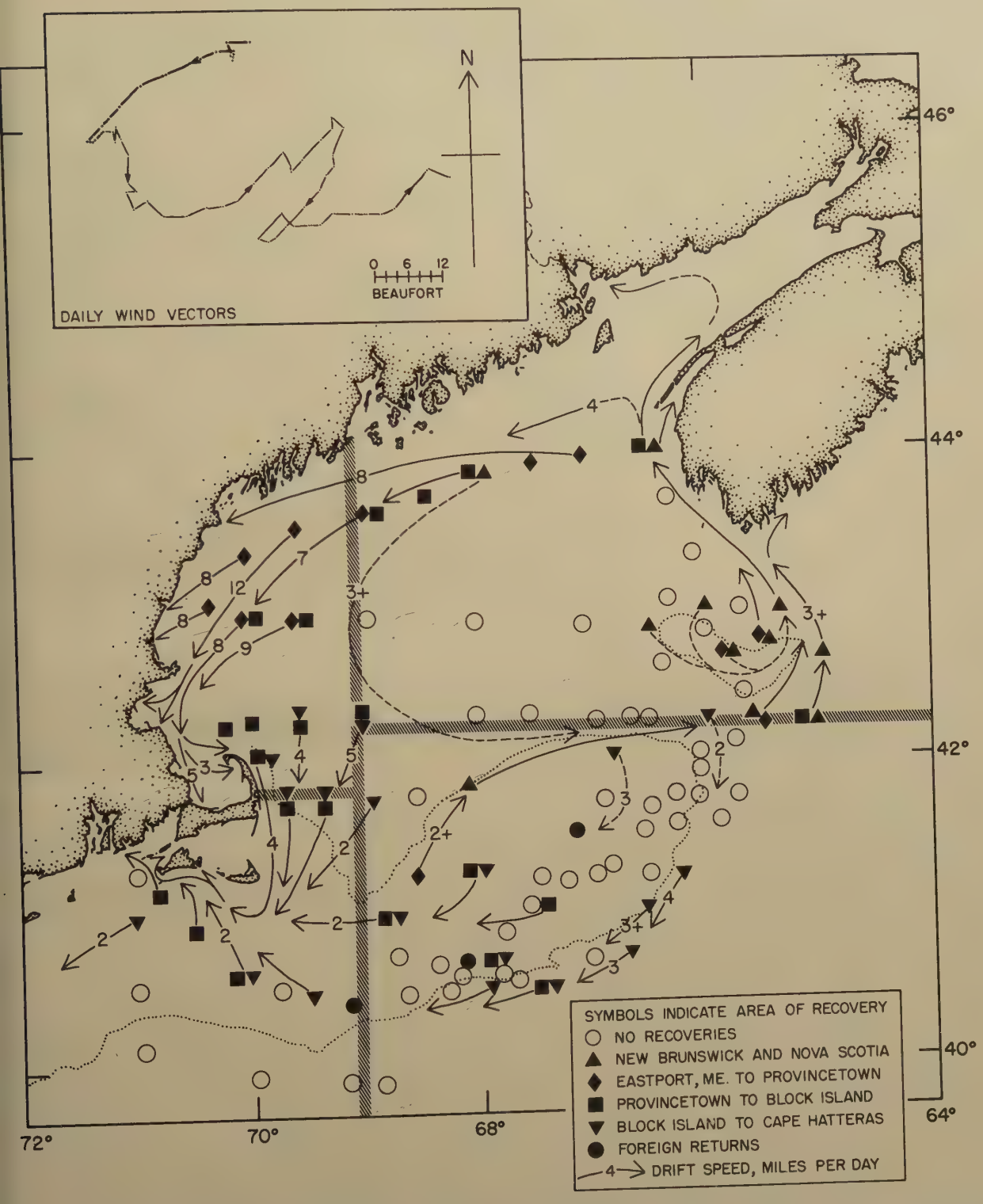

FIGURE 12.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 60, April 19–May 3, 1955.

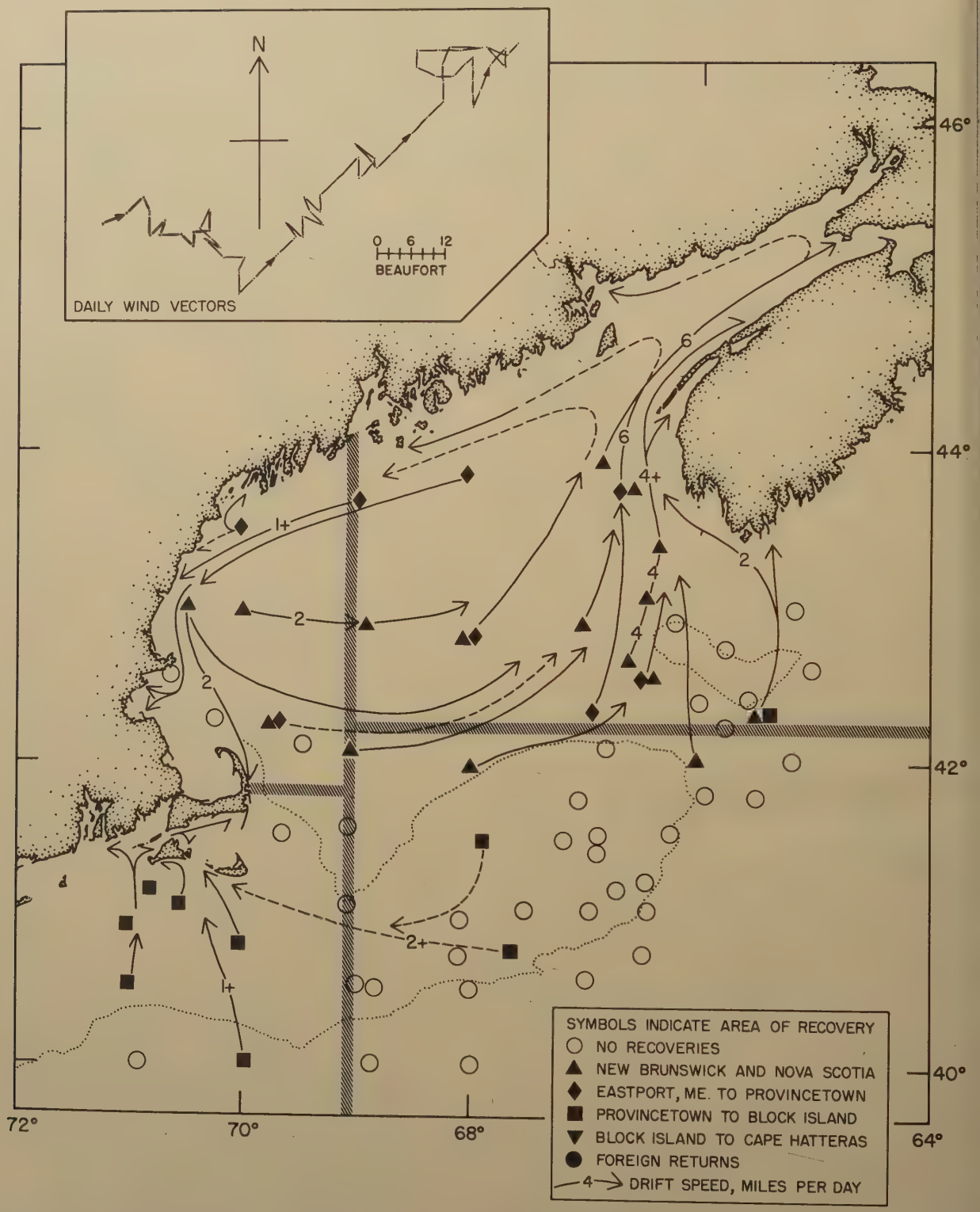

FIGURE 13.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 73 April 17–28, 1956.

931 and 1934, while in 1953 it can be considered present except on the eastern end where movement was probably offshore.

Cruise 60, in 1955, while indicating the presence of both the Georges Bank and Gulf eddies, clearly shows the effect of winds. The continuous northeast winds during the cruise and northerly winds for the 12 days following apparently accelerated water movement along the northern and western edges of the Gulf and greatly augmented the seaward flow through South Channel. The western segment of the Gulf eddy was probably displaced eastward. The winds were not strong enough or of sufficient duration to destroy the northeastward flow of the Georges eddy, however.

Cruise 73, in 1956, shows even more wind dominance. The northwest winds during and for 10 days following the cruise appear to have lasted long enough to move bottles offshore along the western edge of the Gulf and confine the southern edge of the Gulf eddy to the north. Bottles from the eastern half of Georges Bank were moved out of the area, probably to the east, and the presence of a Georges eddy is in question. Movement south of Cape Cod and the islands has a pronounced northerly direction, probably being deflected by the southwest winds starting 11 days after the cruise (see cruises 75 and 76, p. 468).

GROUP *D* CRUISES: LATE MAY AND EARLY JUNE

Albatross II cruise, May 26–28 and June 3–7, 1931 (Figure 14)

The Georges eddy is clearly delineated here, the southwestward movement over the southern part being the most pronounced. The southerly flow out of South Channel is evident, as is the westward flow south of the islands. Winds immediately following the end of the cruise are contradictory.

Albatross III cruise 50, May 25–June 2, 1953 (Figure 15)

From the northern part of area I, the Gulf eddy carried bottles to the tip of Cape Cod at speeds of 5 miles a day and thence northeast into Canadian waters at better than 2 miles a day. From the southern stations, bottles were probably swept offshore into the Georges Bank region by the dominant northerly and westerly winds.

In area II, the southern segment of the Gulf eddy moved slightly northward, there being no returns from South Channel or northern Georges Bank. The northward flow into the Bay of Fundy is represented by returns from four stations, giving a velocity of 4 miles a day.

Area III showed a few scattered returns from stations near shore.

In area IV, cruise 50 is unique among the 17 cruises in that there were no returns from the numerous stations over Georges Bank. While it was in this year (cruises 46, 48, and 50) that some of the ballasted bottles sank (see p. 471), it is still remarkable that none of those without ballast (114 bottles seeded in area IV) have turned up locally or from abroad. The scatter of no-return stations for this cruise indicates a pronounced offshore movement of surface water from the southern Gulf and from Georges Bank to an extent that would have removed any surface eggs and larvae in those regions.

Albatross III cruise 61, May 16–28, 1955 (Figure 16)

The overall picture for this cruise agrees well with Bigelow. The southerly movement through area I and the return flow of the Gulf eddy are both present, as is the flow out South Channel.

Area II shows the eddy complete with speeds of 3 miles a day on the south and east and of 5 miles a day along the coast of Maine.

Surface water drift in area III agrees with Bigelow's diagram, except that the onshore movement south of the islands is again present.

It is probably safe to assume a northeasterly flow along the inner edge of Georges Bank and a seaward movement over the eastern end of the Bank. The southern part has a movement to the westward of 3 miles a day. Returns were had from well offshore which confirms the northwesterly movement apparent in area III.

The northerly component found in area III, and sometimes in area IV, seems to develop when winds are from the west and southwest, as they were during and after this cruise.

Albatross III cruise 75, May 16–29, 1956 (Figure 17)

Area I shows the influence of the dominant offshore wind system during this period. The return flow of the Gulf eddy is clearly marked but is dis-

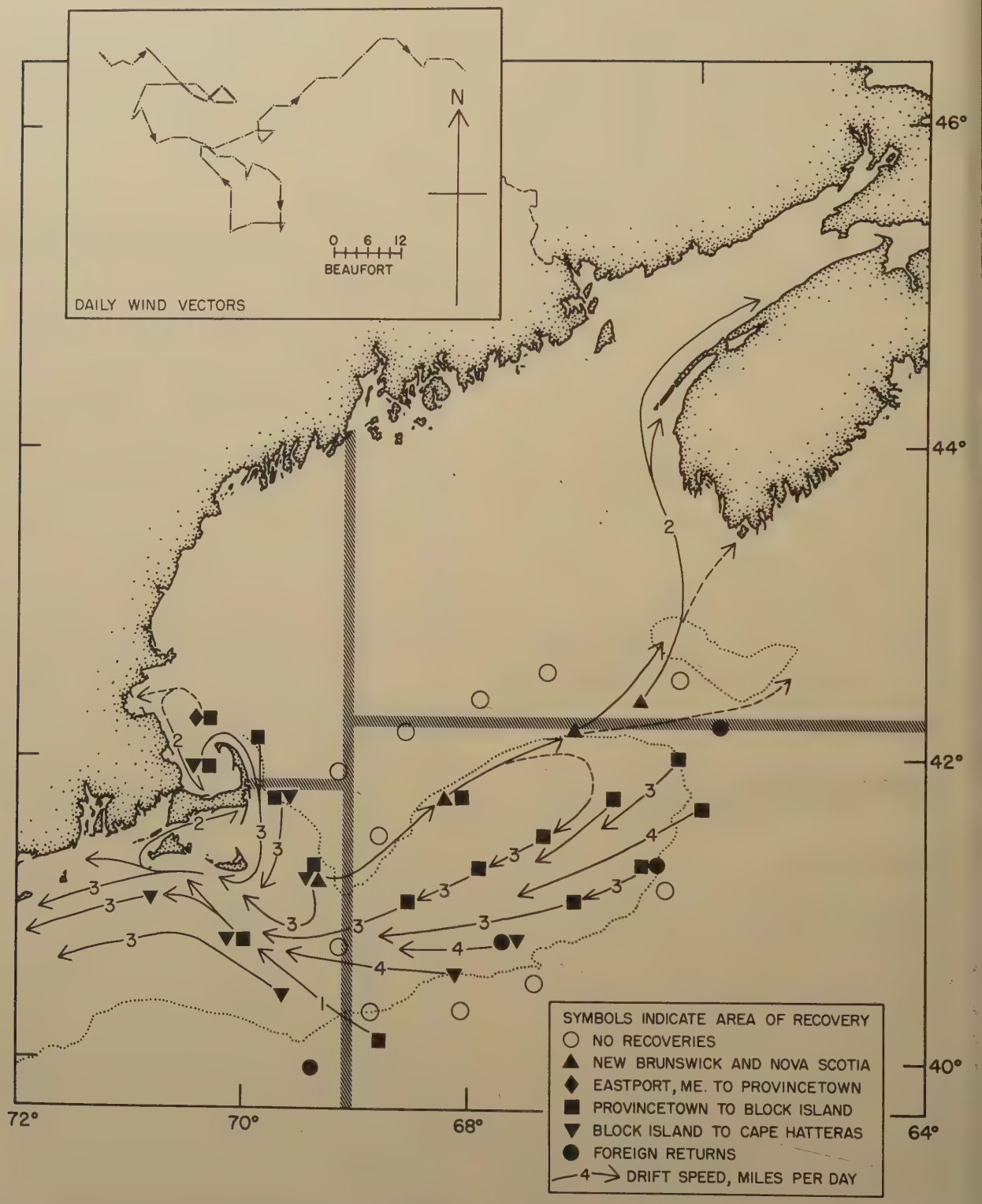

FIGURE 14.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross II*, May 26–28 and June 3–7, 1931.

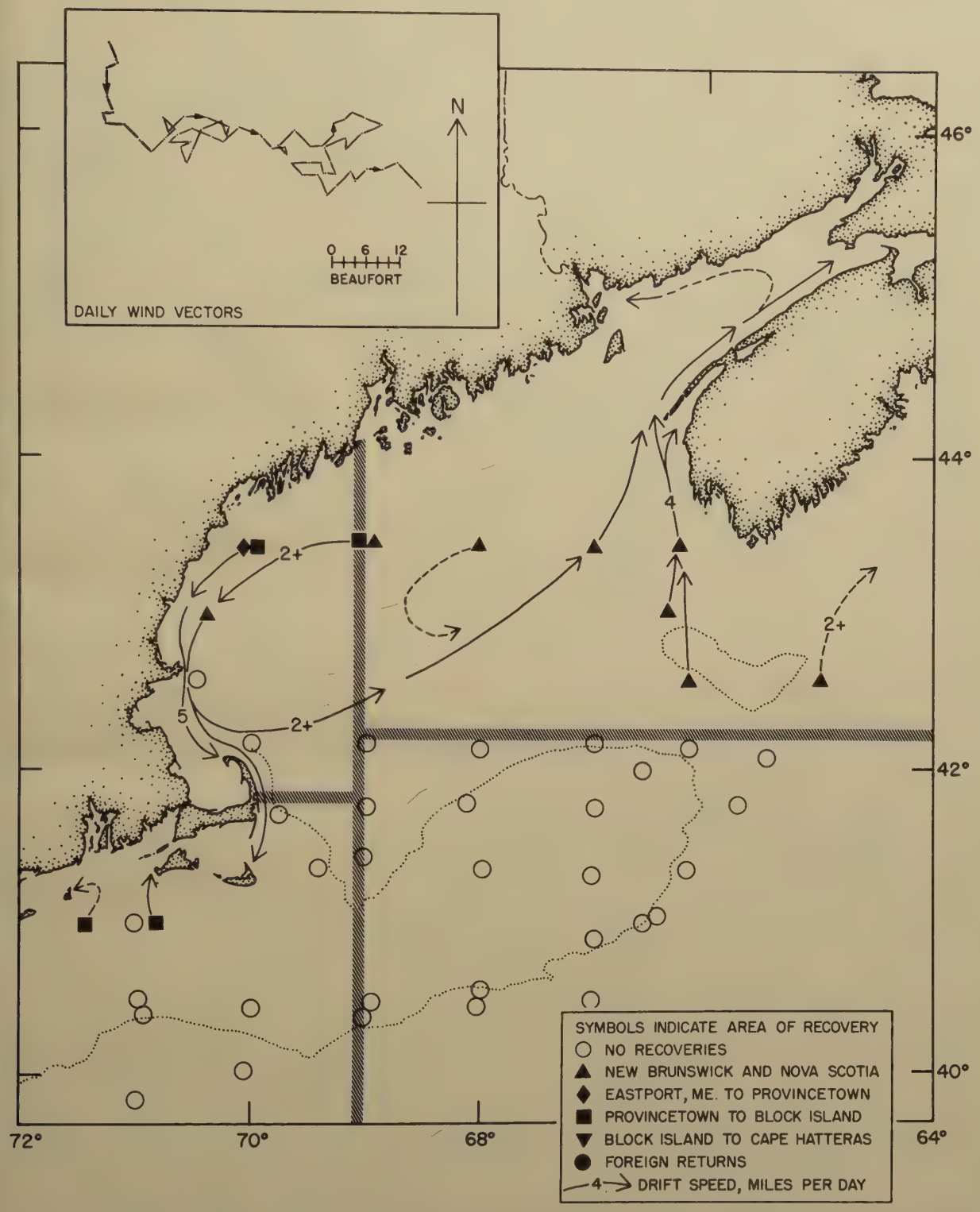

FIGURE 15.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 50, May 25–June 2, 1953.

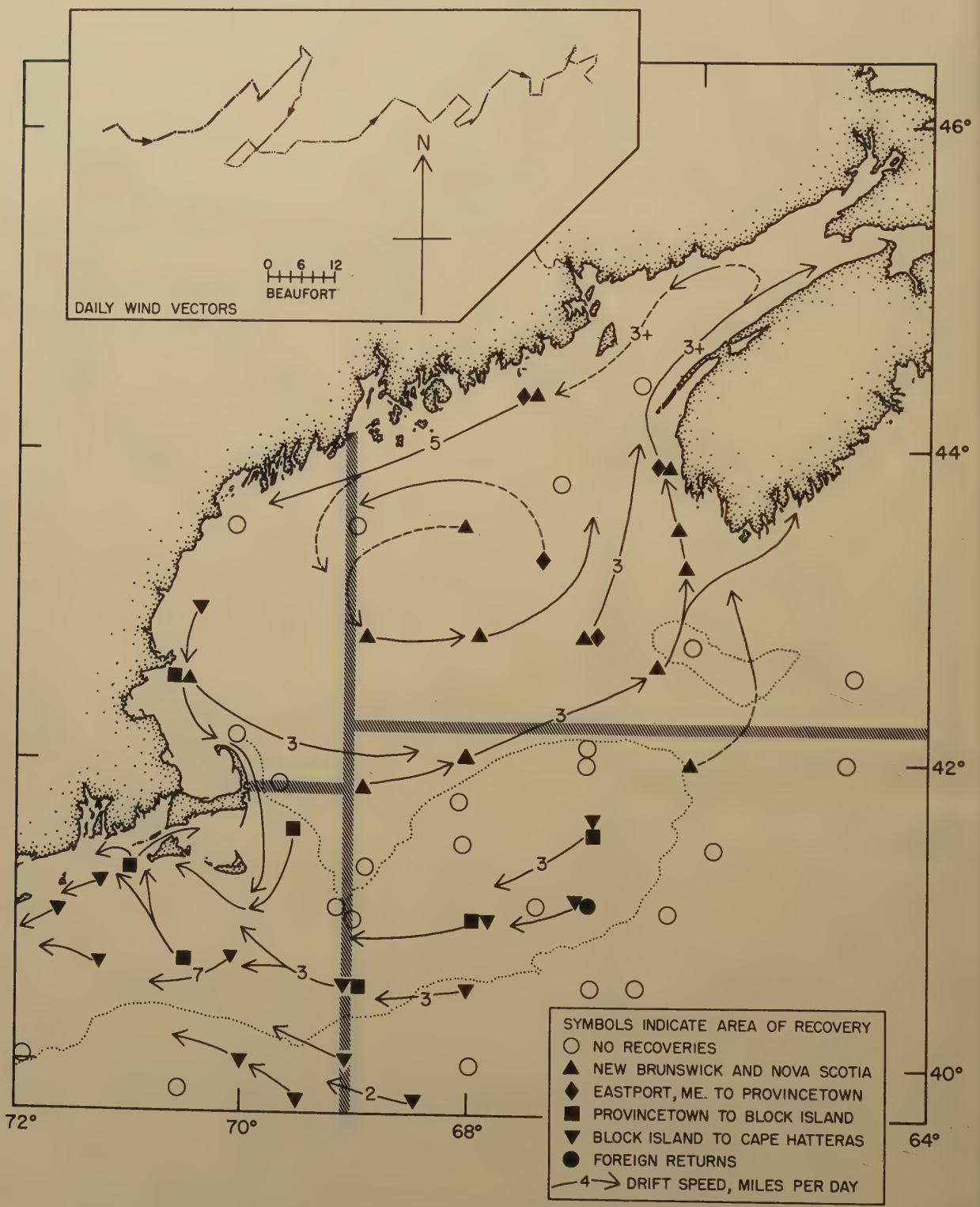

FIGURE 16.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 61, May 16–28, 1955.

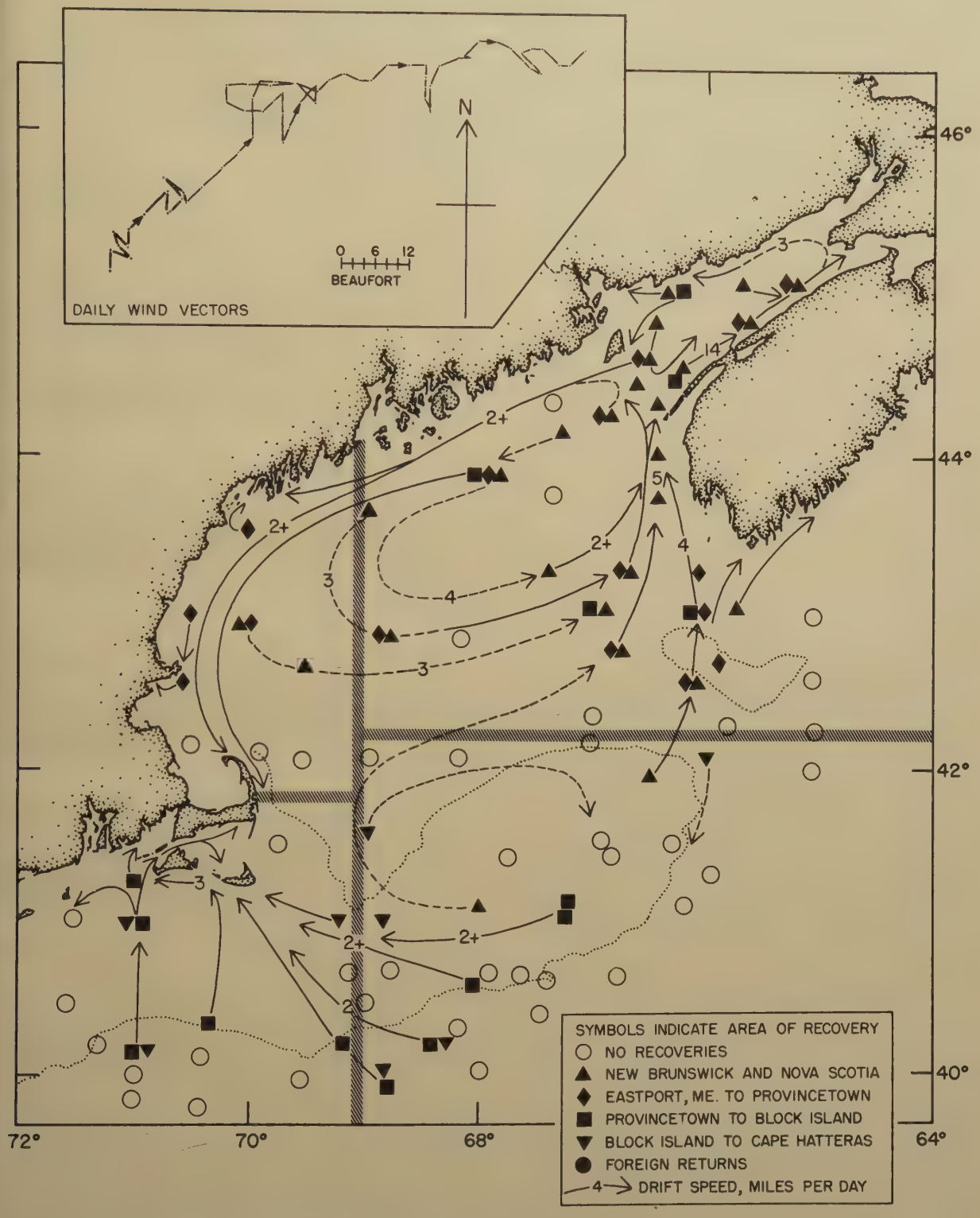

FIGURE 17.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 75, May 16–29, 1956.

placed to the north, while the movement out South Channel is not apparent.

In area II, there is a pronounced northward flow from the region of Browns Bank, with a velocity of 5 miles a day. This increased to a velocity of 14 miles a day along the southeastern shore of the Bay of Fundy. The return flow along the coast of Maine dropped to 2 miles a day.

Area III shows the westward flow pushed sharply onshore and thence, in many cases, to the northeast into Buzzards Bay and the sounds. Southerly flow out South Channel is not apparent.

In area IV, the Georges eddy does not appear. However, it seems reasonable to assume a southeasterly movement from the western and southern Gulf outward across the tip of Georges Bank. Returns from the southern half of the Bank seem to have moved westward and northward exhibiting the same onshore tendency seen in area III.

There is no doubt that the surface movement in the area of study was strongly influenced by the dominant southwest and west wind system here.

Of the four cruises in group *D*, only the first (*Albatross II*) can be considered free from wind influence. Unfortunately, bottles were put out only in the southern portion of the area of study, but from the drift characteristics of these it is fair to assume that the circulation agreed well with the Bigelow diagram. Assuming this is true and that such movement—which we saw developing in the cruises of group *C*—can be considered normal circulation at this season, the following departures from normal in the last three cruises appear:

1. The offshore winds which characterized cruise 50 confined the Gulf eddy well to the north while the Georges Bank–South Channel region was virtually swept clean.

2. Wind vectors for cruise 61 averaged slightly to the south of west and the drift pattern agreed with Bigelow's, with one exception: the westerly flow south of the islands was strongly deflected northward.

3. In 1956 winds during cruise 75 were uniformly from the southwest. They probably served to confine the Gulf eddy to the northeastern part of the Gulf of Maine, piling up water in this region. As we have seen before, winds from this direction again served to give a strong northerly component to the westerly drift from Georges Bank and south of the islands. Surface outflow from the region came from the western Gulf out across the east end of the Banks.

GROUP *E* CRUISES: LATE JUNE

Atlantis cruise 16, June 19–28, 1933 (Figure 18)

The eastern and southern regions of the Gulf of Maine covered by this cruise are in good agreement with the Bigelow norm. The Georges eddy is apparent, as is the northward movement of surface water across Browns Bank. South of the islands in area III the westerly motion lacks the northward set which appears to occur with southwest winds (cf. 1956 cruises).

Albatross III cruise 76, June 11–24, 1956 (Figure 19)

Bottles launched in area I moved eastward into Canadian waters, penetrating well into the Bay of Fundy at a rate of 4 miles a day. Among all the cruises, this cruise represents the best agreement with the Bigelow diagram in this area. The northerly flow from Browns Bank is clearly marked. Thus, the west winds appear to have closed off the Gulf circulation.

In area III, the onshore set seen earlier (cruises 72, 73, and 75) has been intensified and many bottles moved eastward into Vineyard and Nantucket Sounds. Area IV produced few returns, these being from Virginia and North Carolina and indicating, along with the no-return stations, a pronounced movement away from the region.

Of these two June cruises, the first cruise, though of limited coverage, can be said to represent normal circulation for the season and to agree well with the Bigelow diagram, being relatively uninfluenced by winds.

The second cruise, in 1956, which is characterized by fairly consistent westerlies, shows that such winds can be expected to modify the Bigelow norm in the southern portion of the area of study in that movement from Georges Bank will be generally offshore away from the area, and the usual westward flow south of Cape Cod and the islands will be deflected northward and onshore. The surface plankton from the Bank would be lost to the area, while that which may have drifted westward would be moved shoreward.

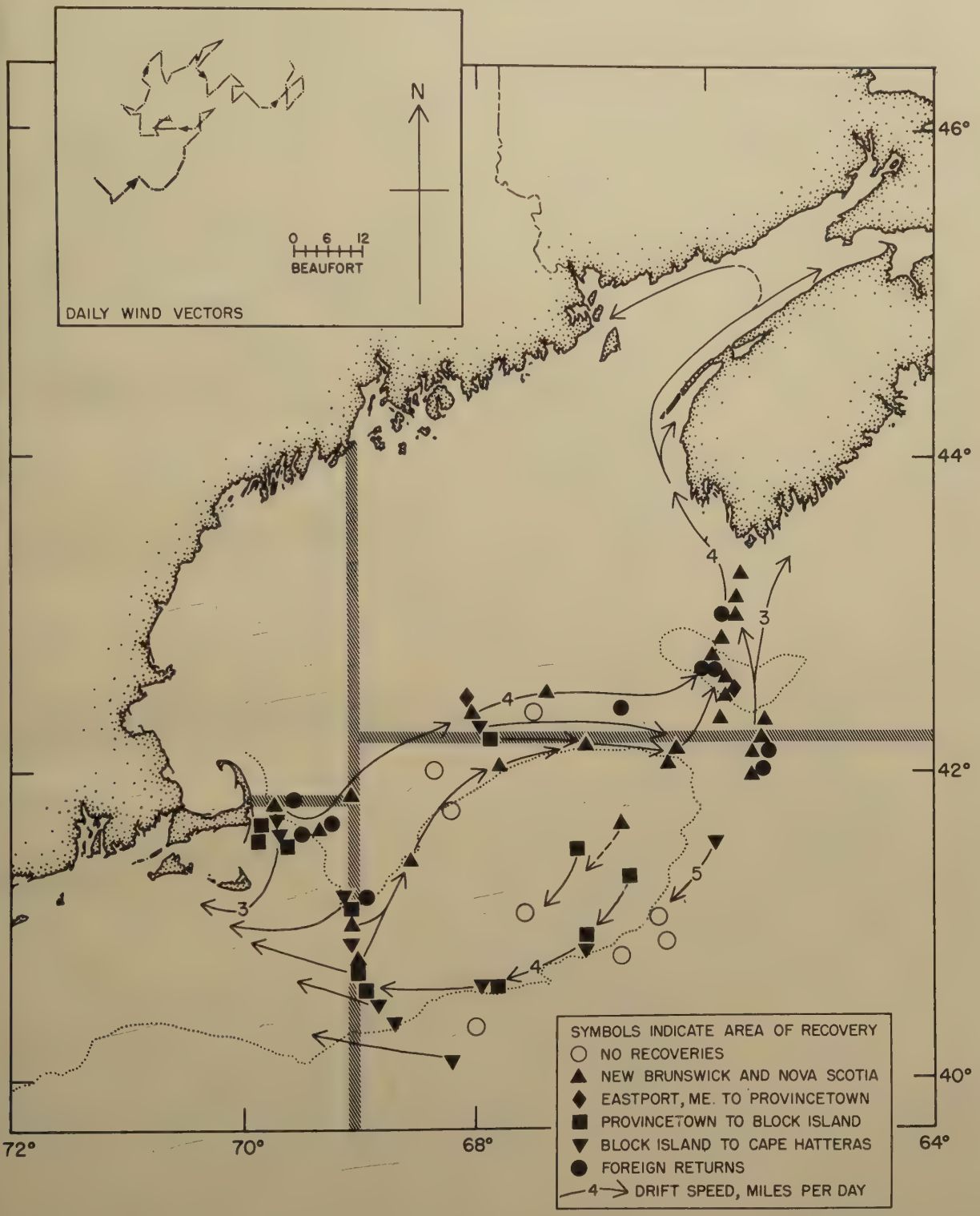

FIGURE 18.—Surface circulation deduced from recoveries of drift bottles launched by *Atlantis*, on cruise 16, June 19–28, 1933.

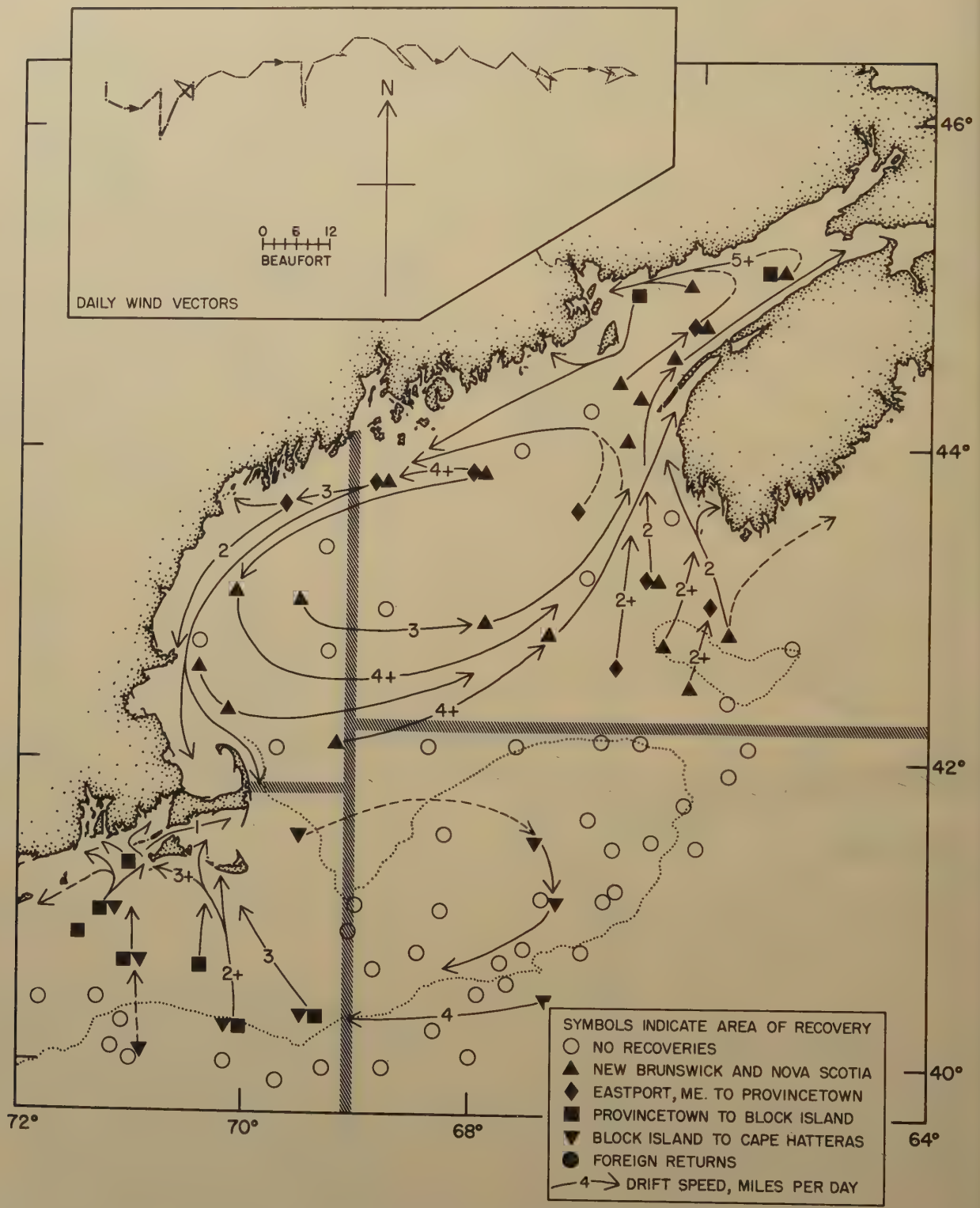

FIGURE 19.—Surface circulation deduced from recoveries of drift bottles launched by *Albatross III*, on cruise 76, June 11–24, 1956.

INDICATIONS OF BOTTOM DRIFT

An interesting and unexpected result of the drift-bottle seedings in the Gulf of Maine is found in the returns for 1953. By a fortunate accident, some of the ballasted bottles apparently sank, either because too much sand had been added or because the bottles themselves were heavier than normal.

The inference that these bottles sank seems justified. In four cases, fishermen stated that the bottles were brought up from the bottom in nets. Thus, it is thought reasonable to assume that the other ballasted bottles found at sea by fishermen also sank, as it is improbable that they could have remained afloat in the same area of swift tidal currents for periods ranging from 4 to 37 months.

The net direction and distance of drift of 12 of these bottles are shown in figure 20. In only two instances is there any indication of rate of drift: bottle No. 13339 shows a net movement of 1 mile a day and No. 13827 of 0.7 mile a day. Of interest is the uniform picture of southwesterly movement of water at the bottom along the southern edge of Georges Bank and the general southerly movement out South Channel. This, in general, fits well with the surface water movement in these areas.

CONCLUSIONS

A consideration of the 17 cruises in the Gulf of Maine from the point of view of the conditions tending to conserve or disperse planktonic forms within the region of study leads to three conclusions.

1. Bigelow's (1927, pp. 972–3) July–August pattern, a relatively closed circulation and hence highly conservative, seems to evolve with the seasons, possibly as a result of vernal warming and the consequent formation of density structure. In February and March, the Gulf eddy is ill-defined on the south as water from area I moves seaward out South Channel. The Georges eddy is not apparent, the net movement of surface water being southwest. By late April, the two counterrotating

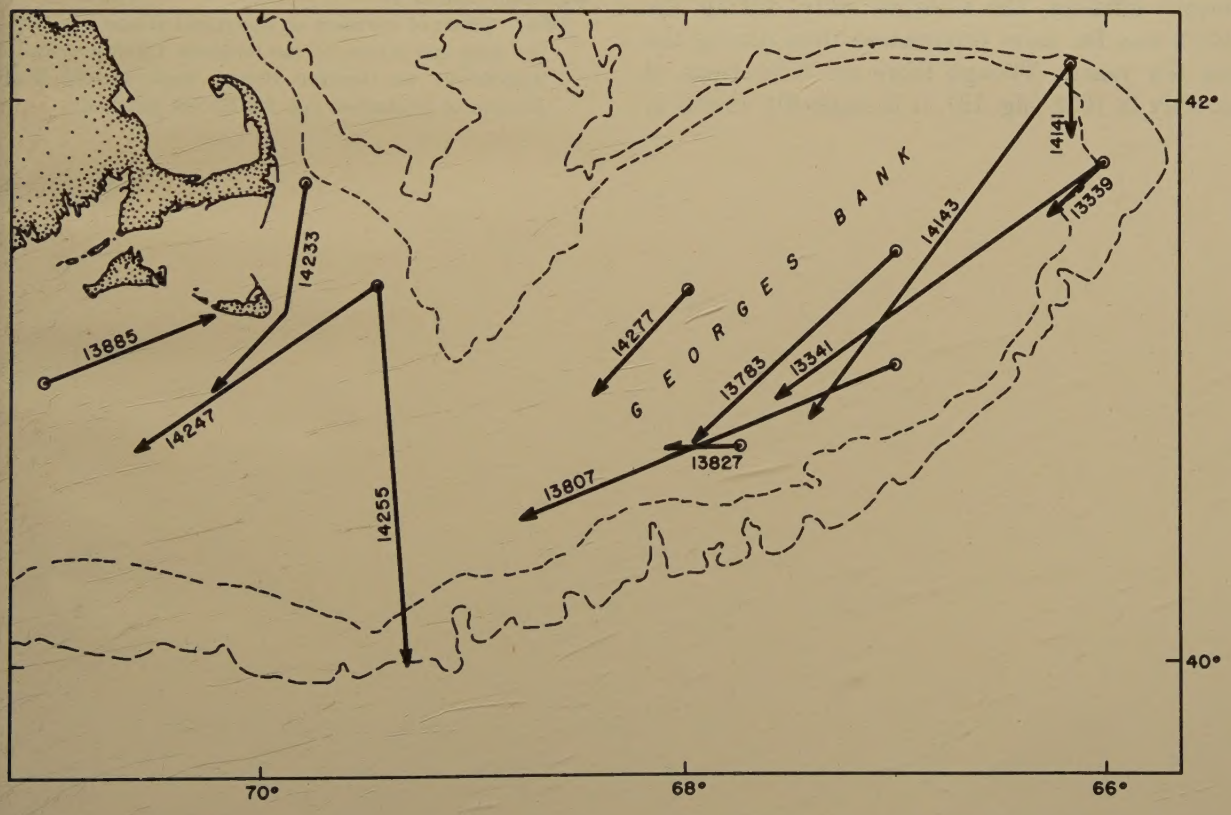

FIGURE 20.—Net movement of drift bottles which apparently sank and were recovered from the bottom by fishermen.

eddies are taking form with the appearance of a northeasterly movement along the northern edge of Georges Bank where the two eddies become confluent. After this development, plankton within the Gulf would probably be retained.

2. At any time during the seasons considered, the prevailing circulation may be strongly modified by winds. Offshore winds from the northwest quadrant have a pronounced effect on the Georges Bank region, tending to destroy the eddy (figs. 3, 4, 8, and 15). Northeasterly winds, even of short duration as during cruise 60 of the *Albatross III* (fig. 12), speed up the northern segment of the Gulf eddy and increase the flow out South Channel. Winds from the west and southwest (figs. 13, 16, 17, and 19) seem to give a strong onshore component to the waters south of Cape Cod and to accentuate the northward flow from Browns Bank into the Bay of Fundy.

3. In the region of Georges Bank, a marked difference between conditions in the 1930's and 1950's is apparent. With the exception of the April cruise of 1932 (fig. 8), when winds were uniformly offshore, the Georges eddy during the 1930's was far more pronounced than during the last few years. Though there are indications of an eddy in 1955 (fig. 12), it is markedly absent in 1953 and 1956 (figs. 4, 5, 7, 11, 13, 15, 17, and 19). Plankton on the Bank had more chance of surviving locally in the early 1930's than in 1953 and 1956.

Efforts to assess the potential of any given spawning season within the area should certainly involve accurate knowledge of the time and places of spawning and a careful consideration of wind patterns during the period of the planktonic stages of the fish in question.

REFERENCES

BIGELOW, HENRY B.,
1927. Physical oceanography of the Gulf of Maine. Bull. United States Bureau of Fisheries, vol. 40 (1924), Pt. II, Doc. No. 969, pp. 511–1027.

BUMPUS, DEAN F., and C. GODFREY DAY.
1957. Drift bottle records for Gulf of Maine and Georges Bank, 1931–56. United States Fish and Wildlife Service, Special Sci. Rept.: Fisheries No. 242, 61 pp.

EKMAN, V. WALFRID.
1902. Om jordrotationens inverkan på vindströmmar i hafvet. Nyt Magazin for Naturvidenskaberne, bd. 40, S. 37–63. Christiania.

WALFORD, LIONEL A.
1938. Effect of currents on distribution and survival of the eggs and larvae of the haddock (*Melanogrammus aeglefinus*) on Georges Bank. Bull. United States Bureau of Fisheries, vol. 49, No. 29, pp. 1–73.

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